Agenda	East Coast	West Coast
Executive Session	8:30	5:30
Perlmutter - Overview, Supernova Science Observation Strategy 45 min + 10 min questions	9:00	6:00
Turner - Omega, Lambda, Lambda-dot, Q 30 min + 5 min questions	9:55	6:55
Break - 10 min.		
Smoot - CMB (by phone) 10 min.	10:50	7:50
Aldering - Systematics, Calibration, Data Package, Comparisons 35 min + 10 min questions	11:00	8:00
Levi - Instrumentation, Optics, Imager, Technology, R&D, Cost, Schedule 30 min + 10 min questions	11:45	8:45
Lunch - 35 min.	12:25	9:25
Harvery - SSL/LOI 15 min	1:00	10:00
Heetderks - Spacecraft, Mission Ops. 10 min	1:15	10:15
Perlmutter - Wrapup 10 min	1:25	10:25
Executive Session 90 min	1:35	10:35

Fundamental Questions:

- *Will the universe last forever?*
- *Is the universe infinite?*
- *What is the universe made of?*

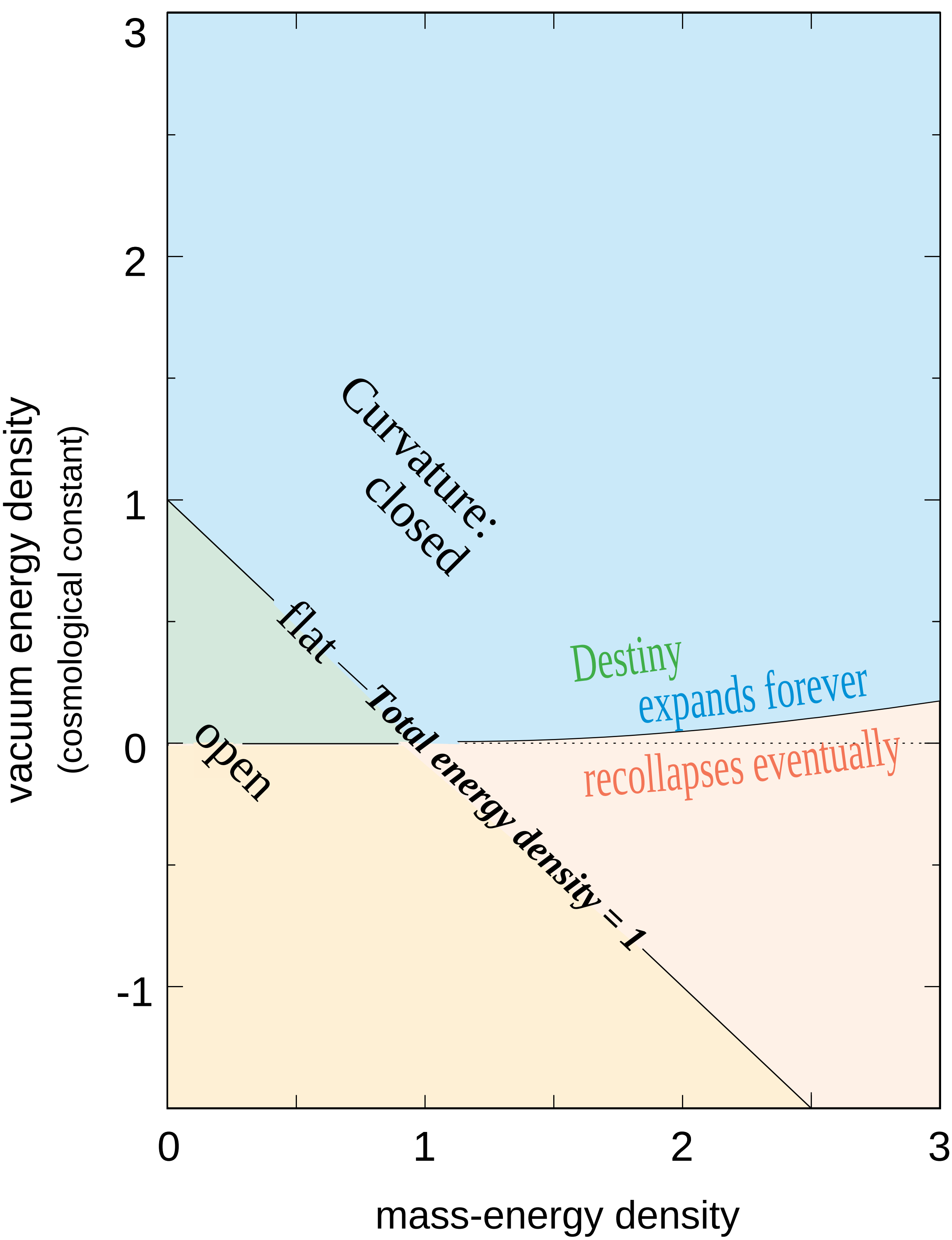
An unusual moment in human history:

At the beginning of this century, Einstein developed the conceptual tools to address these questions empirically.

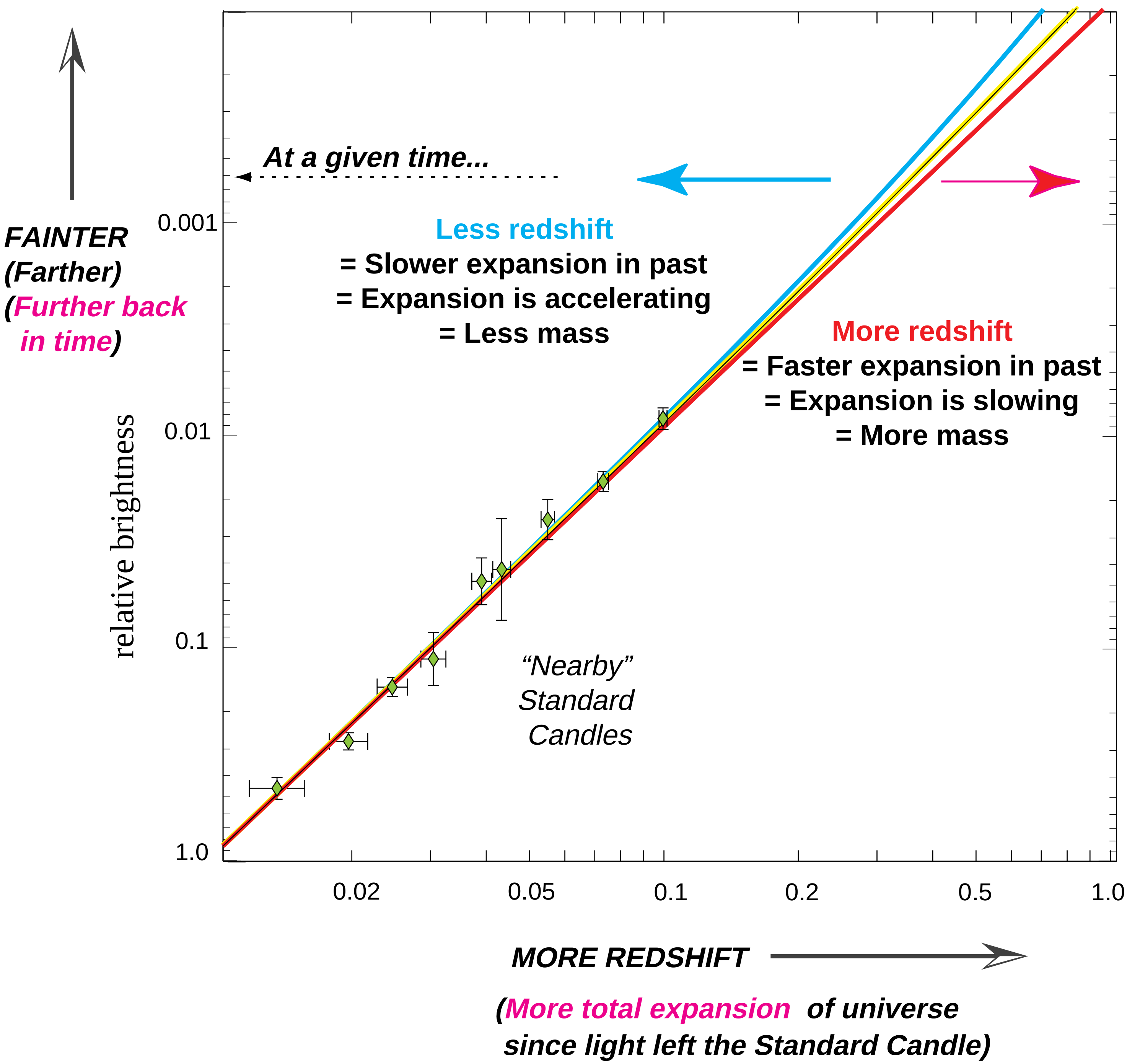
In the past decade or so, technology has advanced to the point that we can now make the measurements that begin to answer these fundamental questions.

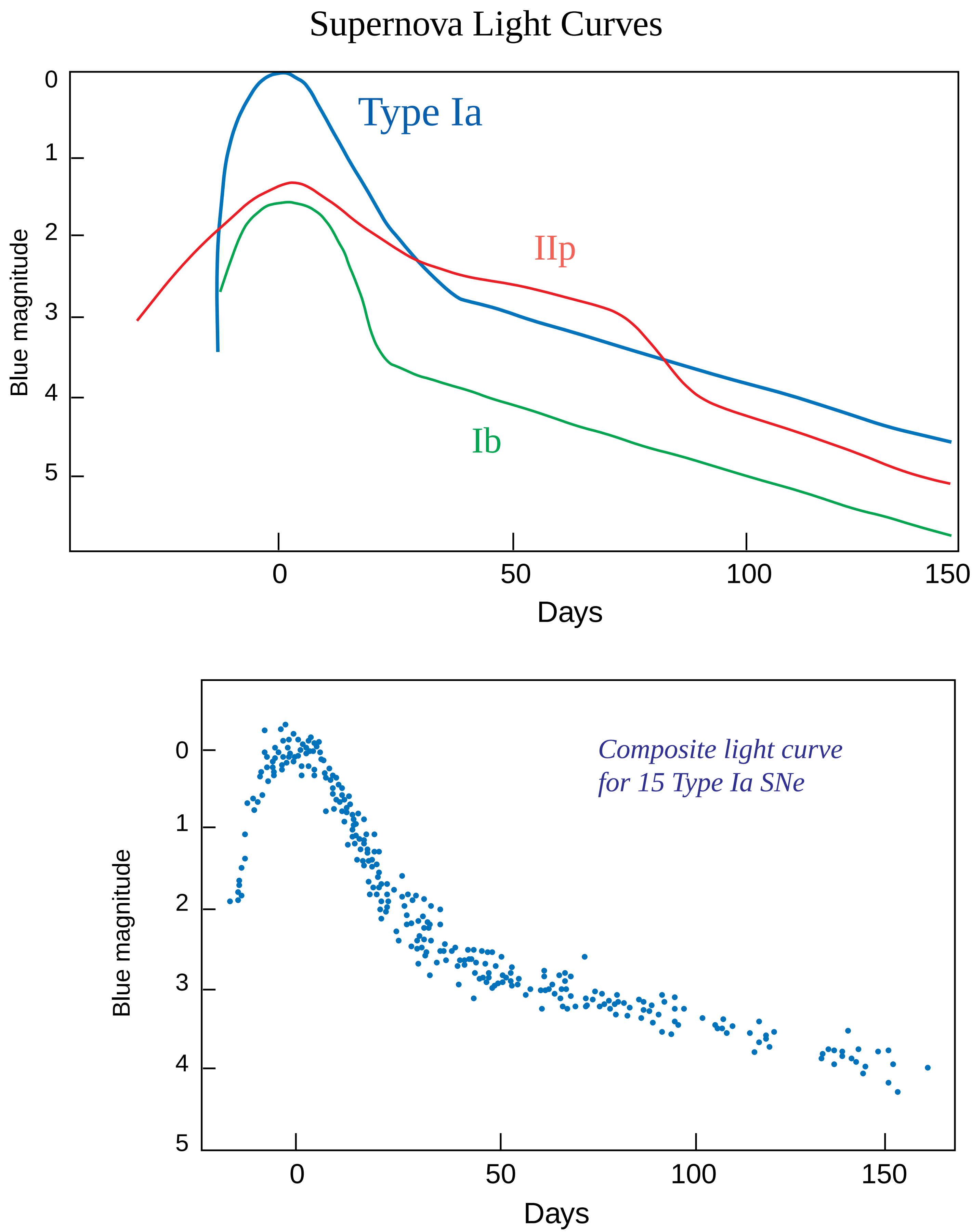
Progress is now being made with large scientific programs, including the supernova cosmology measurements, the Sloan Digital Sky Survey, and the Cosmic Microwave Background satellites: COBE, MAP, and PLANCK

Fundamental questions
—the geometry and destiny of the universe—
are addressed by determining its energy constituents



The Hubble Plot:
A history of the "size" of the Universe

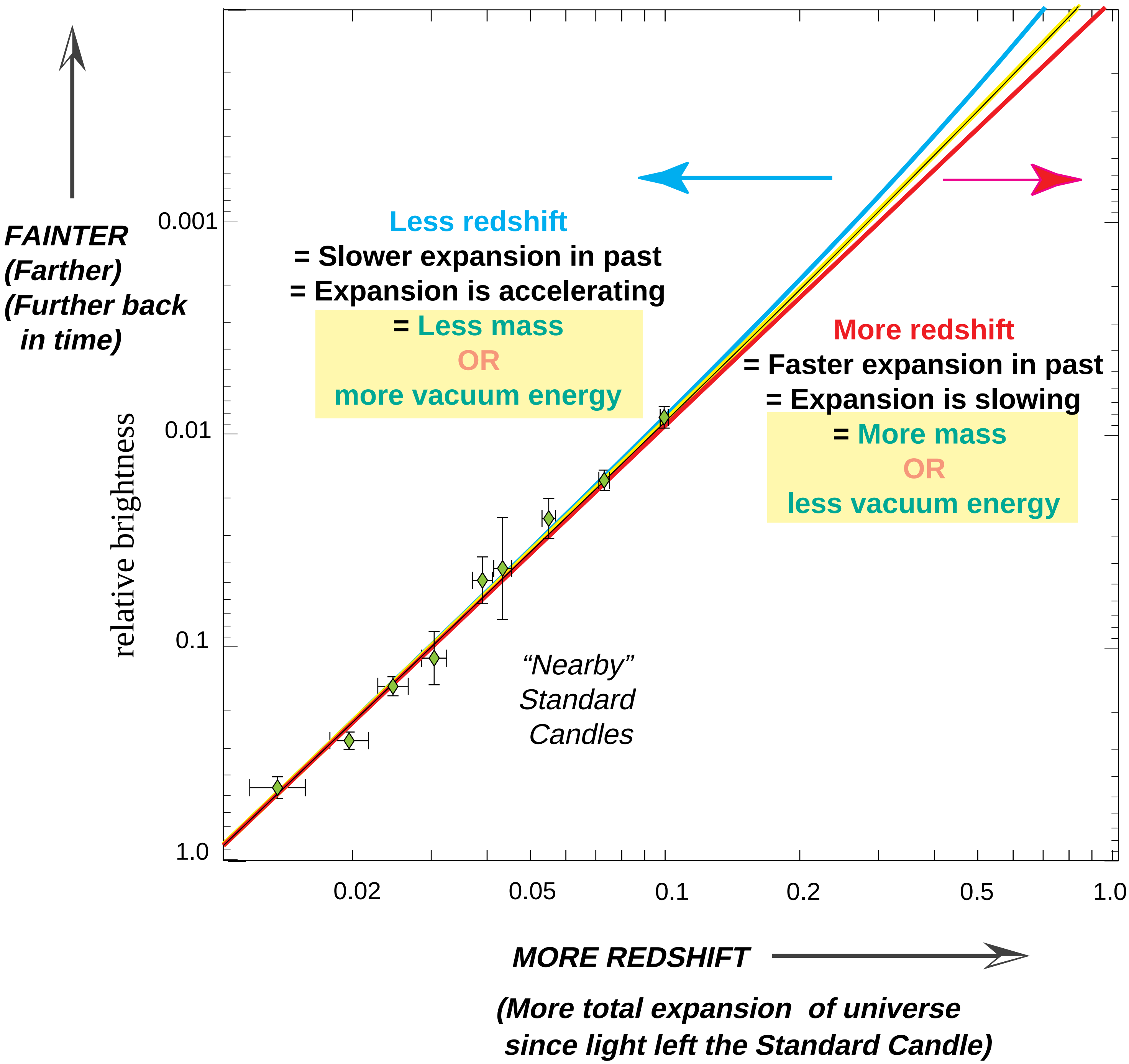


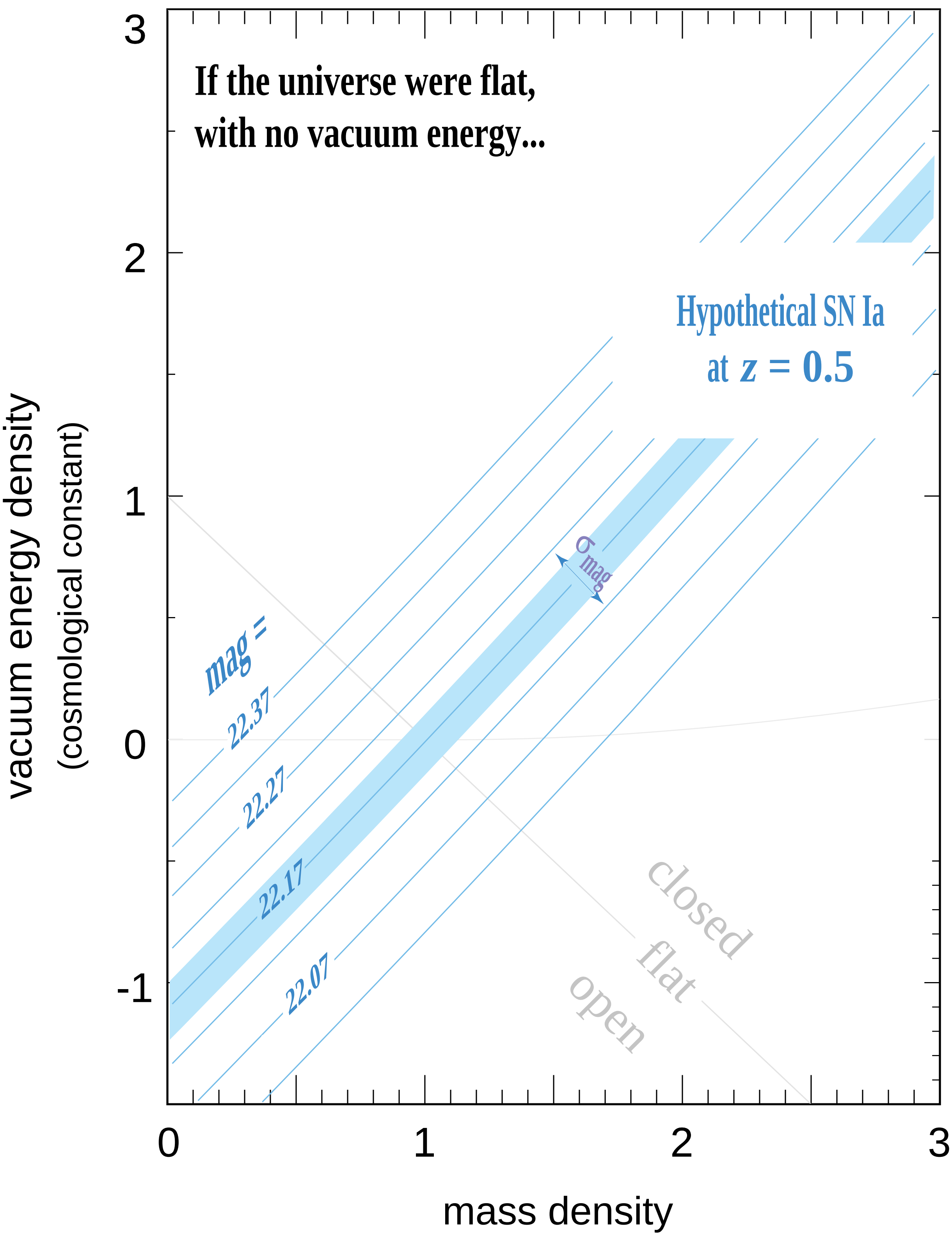


Supernova Light Curves
Type Ia
IIp
Ib
Blue magnitude
Days
0
1
2
3
4
5
0
50
100
150
Composite light curve
for 15 Type Ia SNe
Blue magnitude
Days

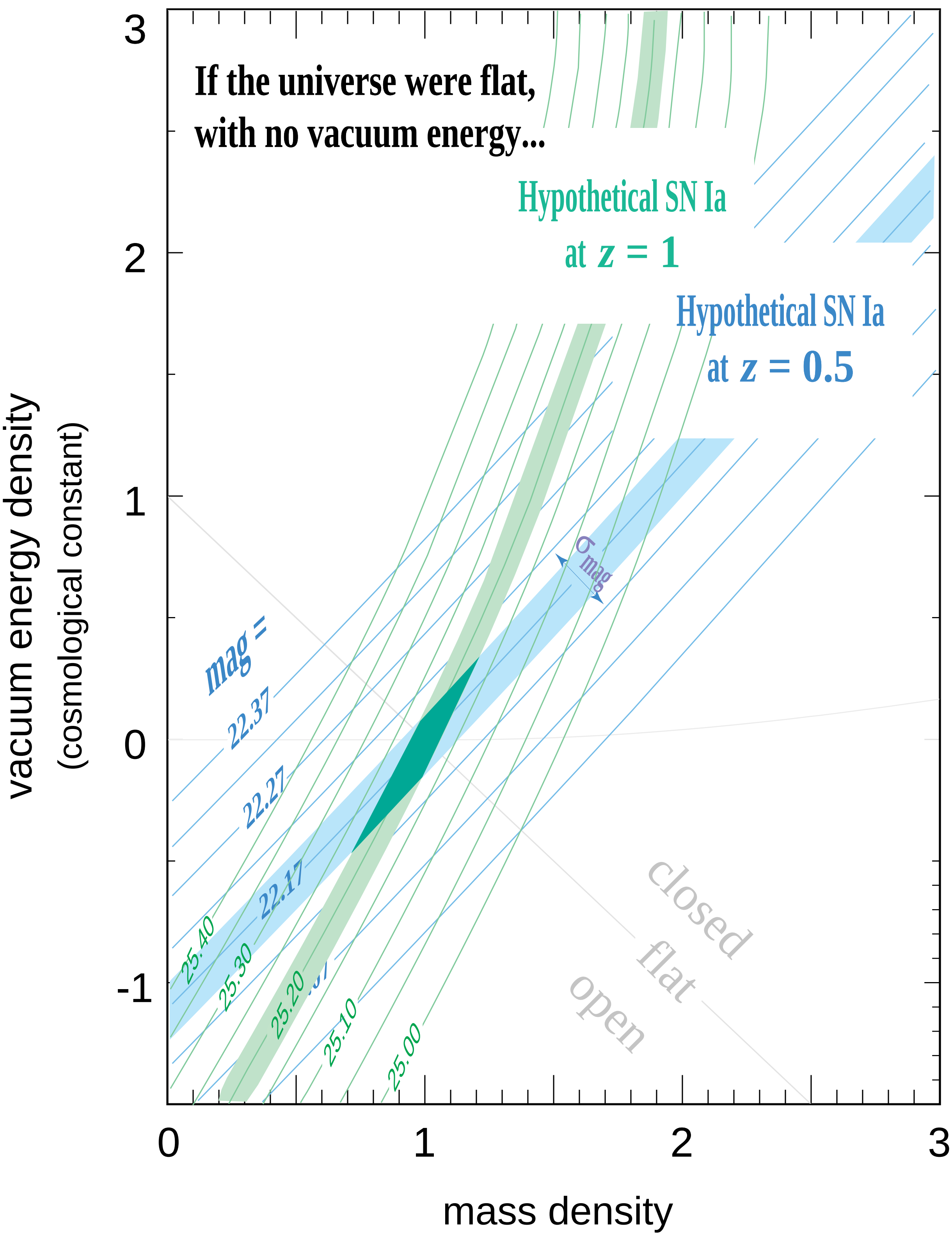
The expansion history provides a direct method to measure mass density and vacuum energy density...

...but how do you tell if you have more of one or less of the other?





Goobar & Perlmutter
(Ap.J. 1995)



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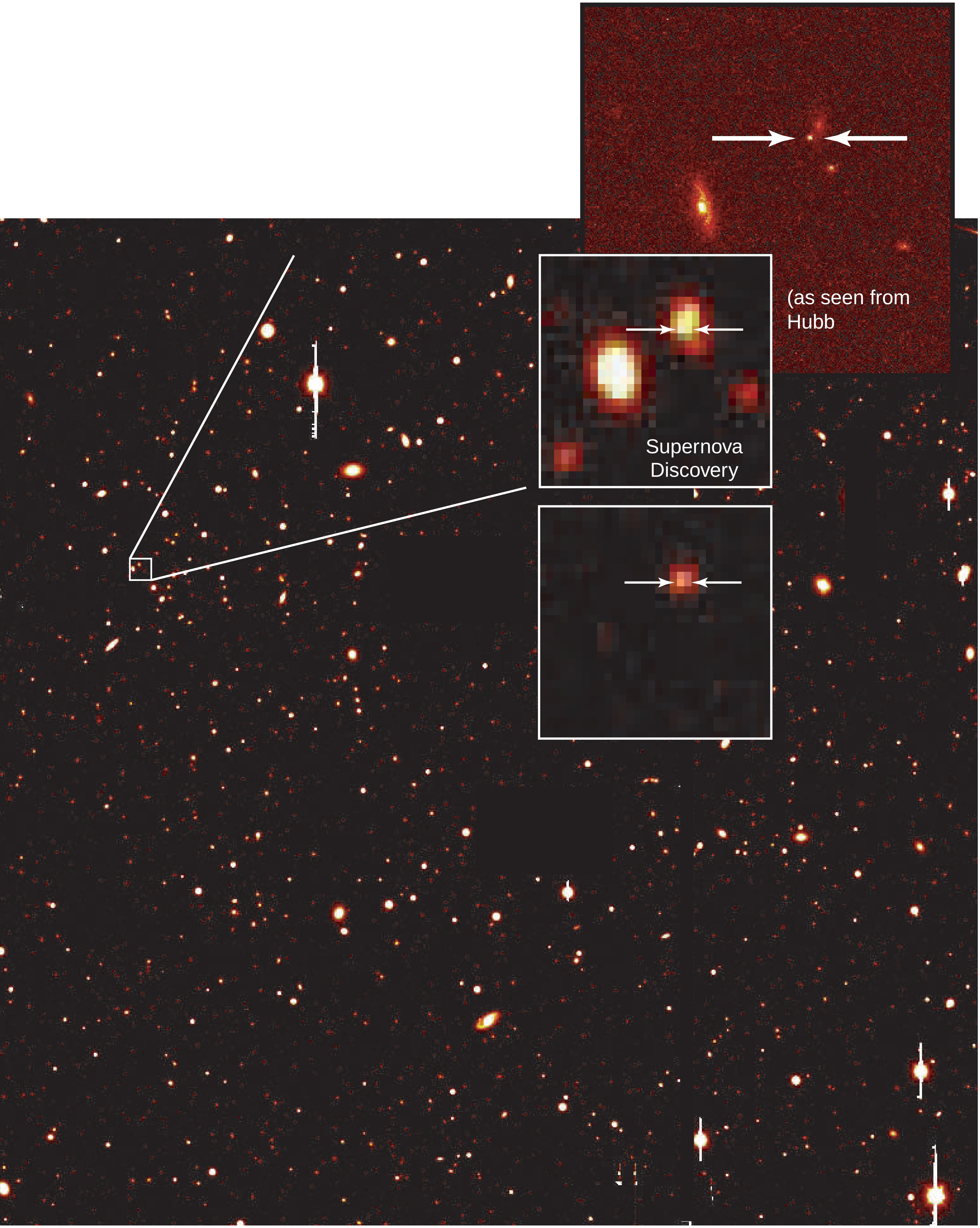
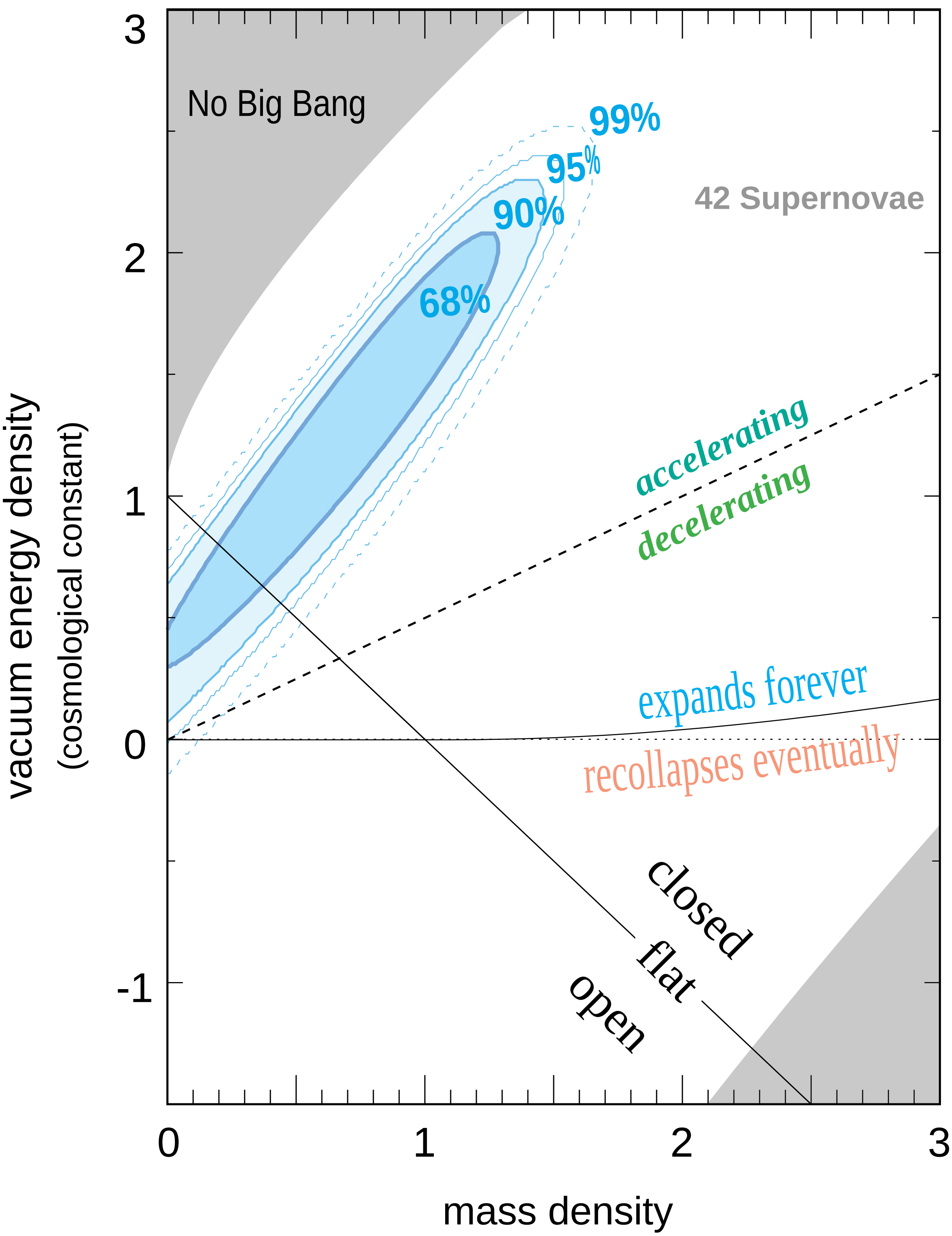
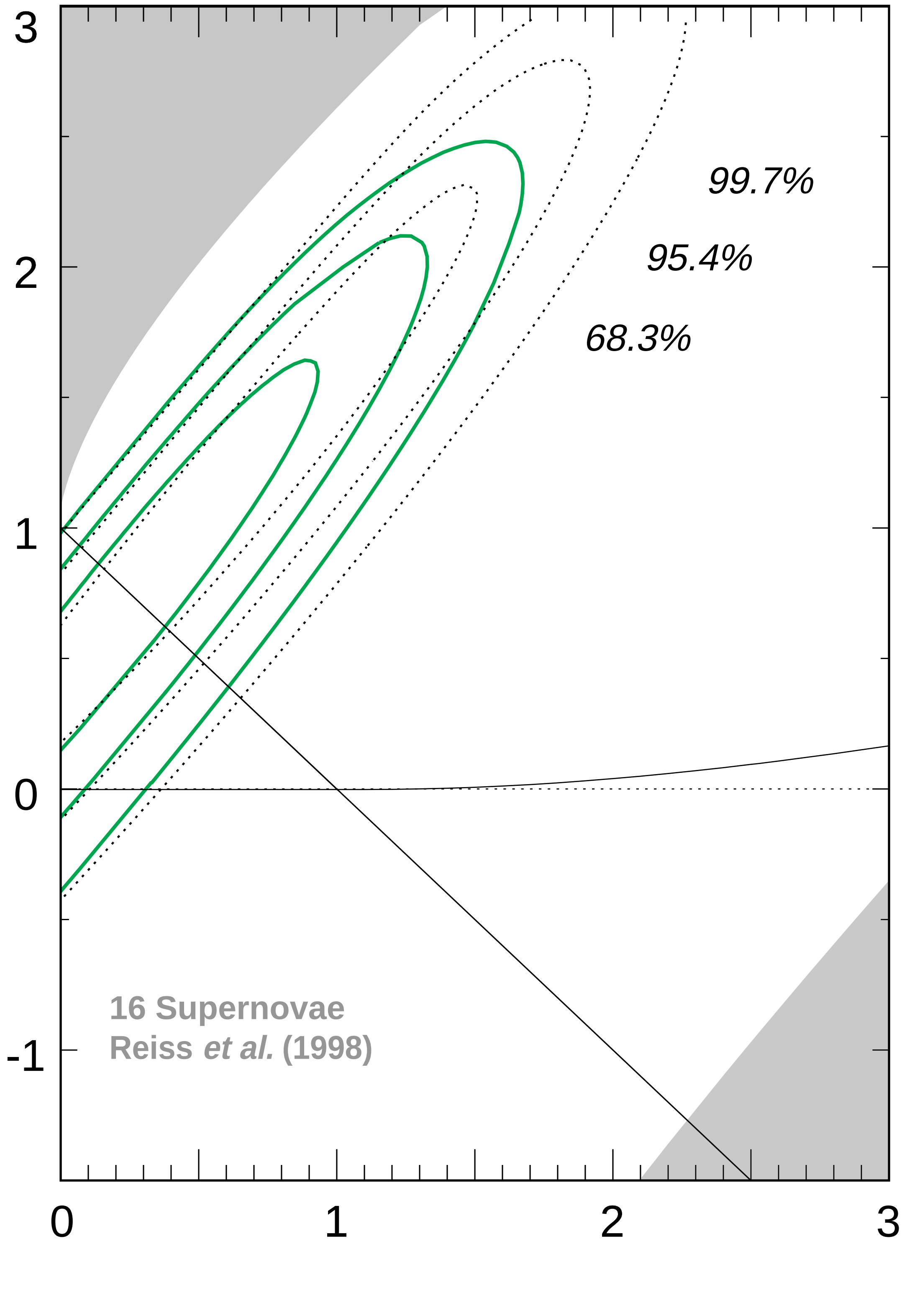

(as seen from
Hubb
Supernova
Discovery

Supernova results confirming earlier hints that there is an accelerating energy.



Supernova Cosmology Project
Perlmutter *et al.* (1998)

Ap.J.
astro-ph/9812133


99.7%
95.4%
68.3%
16 Supernovae
Reiss *et al.* (1998)
3
2
1
0
-1
0
1
2
3

The implications of an accelerating universe:

1. The expansion is not slowing to a halt and then collapsing (i.e., the universe is *not* "coming to an end"). In the simplest models, it will expand forever.

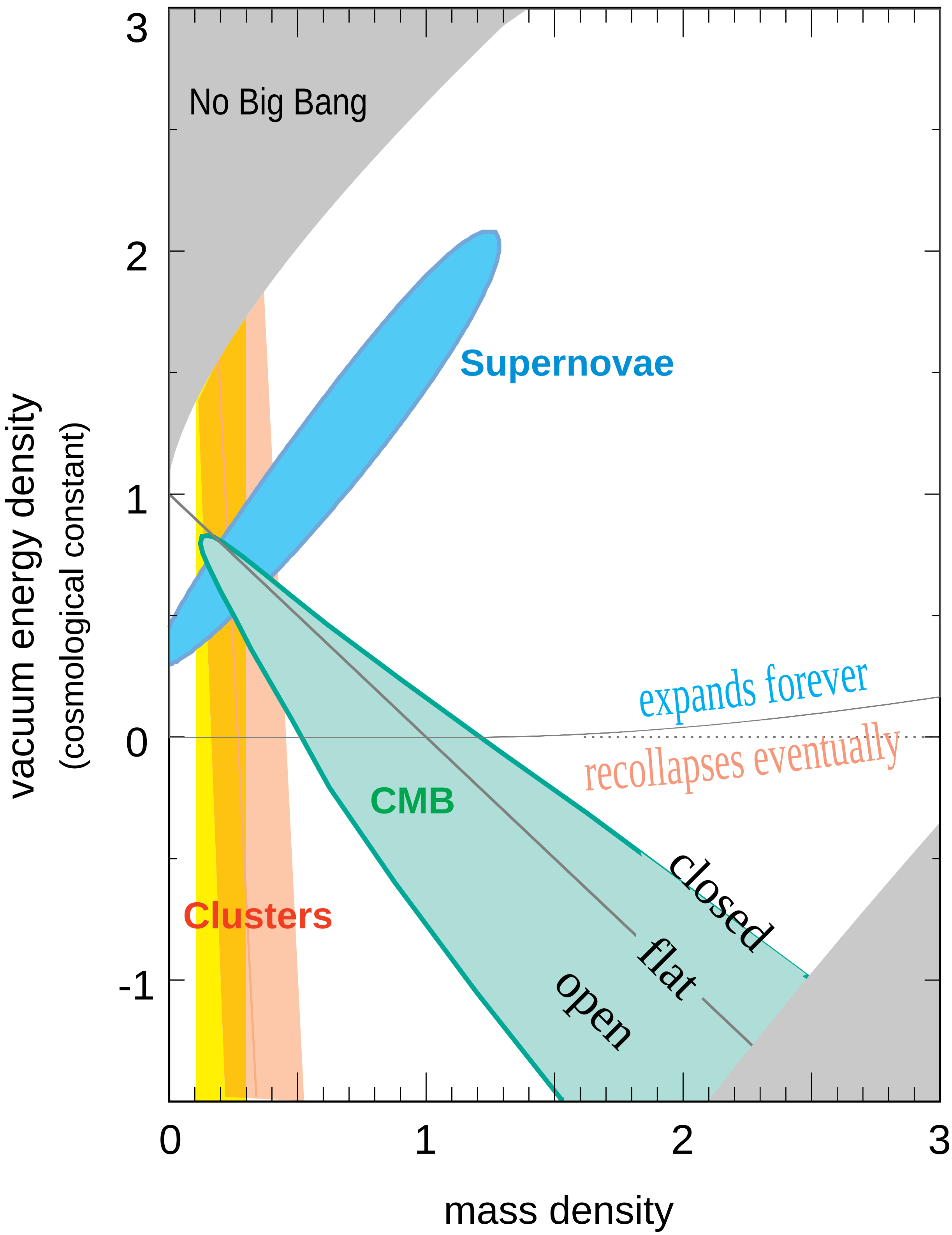
2. There is a previously unseen energy pervading all of space that accelerates the universe's expansion.

   This new accelerating energy ("dark energy") has a larger energy density than the mass density of the universe (or else the universe's expansion wouldn't be accelerating).

What we don't know is:

1. How much of mass density and dark energy density is there? I.e., how much dark matter and dark energy do we need to look for?
   The answer to this question determines the "curvature" of the universe, and can tell us about the extent of the universe: infinite or finite.

2. What is the "dark energy"? Particle physics theory proposes a number of alternatives, each with different properties that we can measure. Each of the alternative theories raises some important questions/problems of fundamental physics.



No Big Bang
Supernovae
expands forever
recollapses eventually
CMB
closed
flat
open
Clusters
vacuum energy density
(cosmological constant)
mass density
3
2
1
0
-1
0
1
2
3

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What's wrong with a non-zero vacuum energy / cosmological constant?

Two coincidences:

- ***Why so small?***

  Might expect $\frac{\Lambda}{8\pi G} \sim m^4_{\text{Planck}}$

  This is off by ~120 orders of magnitude!

- ***"Why now?"***

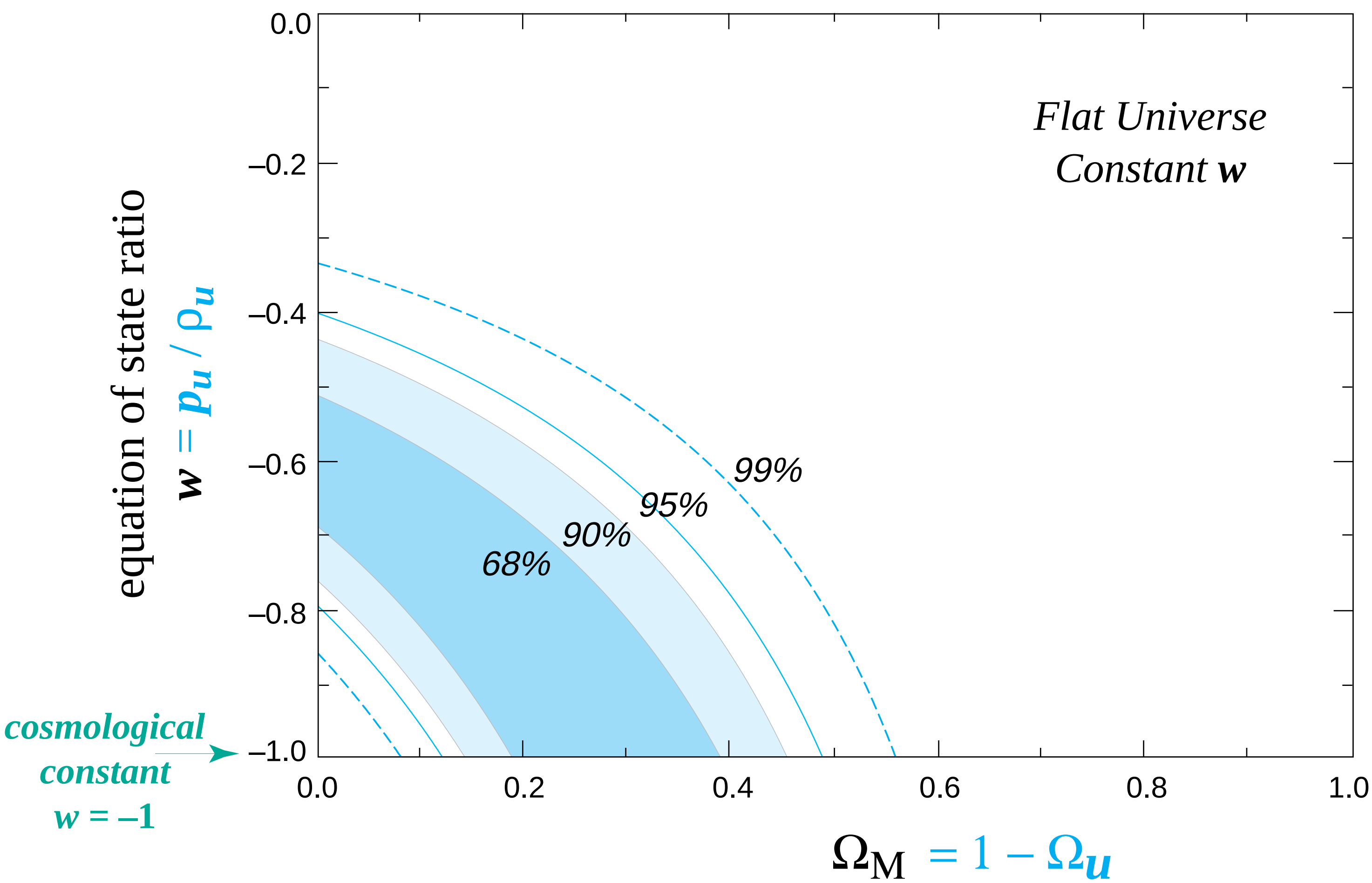
$$\frac{\ddot{R}}{R} = -\frac{4\pi G}{3}(\rho + 3p)$$

MATTER: $p = 0 \longrightarrow \rho \propto R^{-3}$

VACUUM ENERGY: $p = -\rho \longrightarrow \rho \propto \mathit{constant}$

Unknown Component, Ω_u, of Energy Density

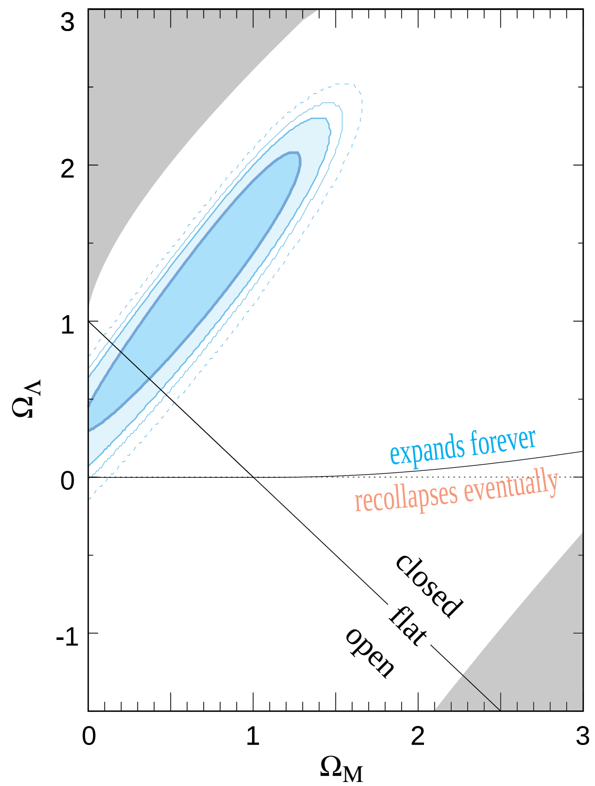
Perlmutter *et al.* (1998)



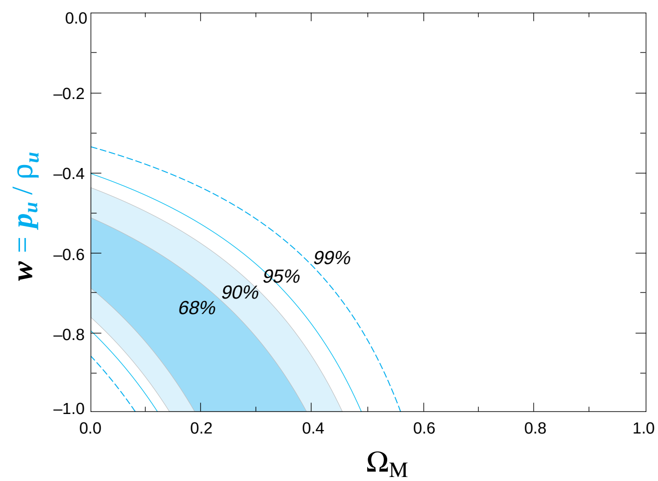
c.f. Garnavich et al. (1998)

How can we address these new questions?

Greatly improve:



and:



...And look for details of w(z).

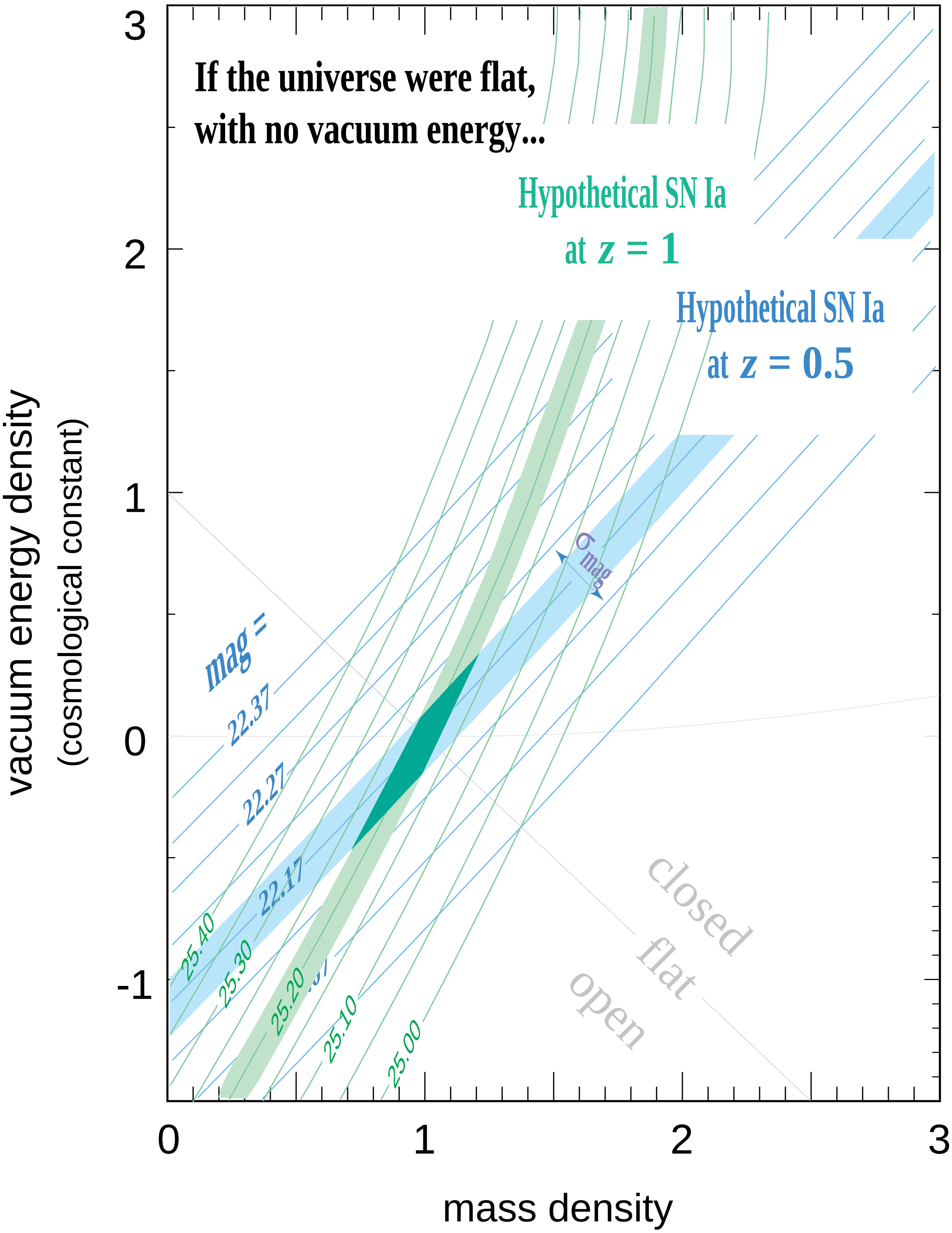
It is necessary but NOT sufficient to find and study

- more SNe Ia
- farther SNe Ia

because the statistical uncertainty is already within a factor of two of the systematic uncertainty:

Best fit in flat universe:

Ω_M = 0.28
Ω_Λ = 0.72 ± 0.09 statistical ± 0.05 systematic



Goobar & Perlmutter
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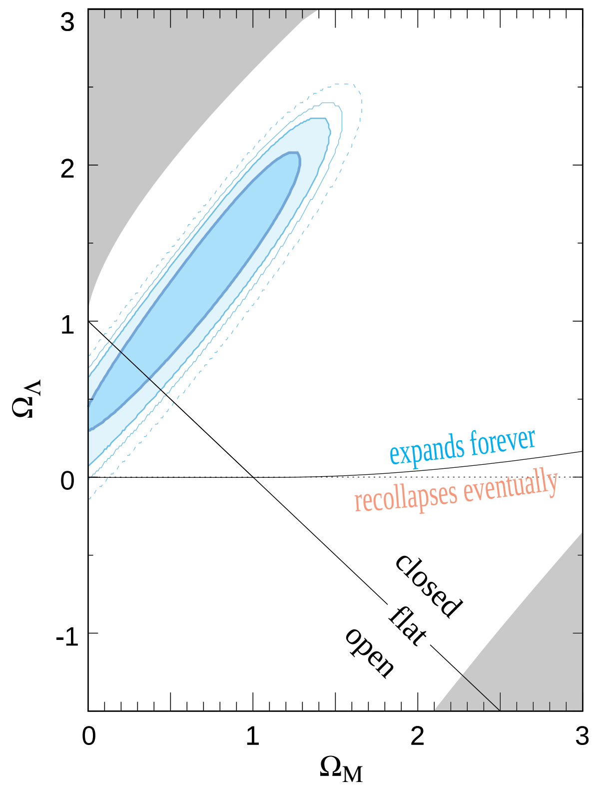

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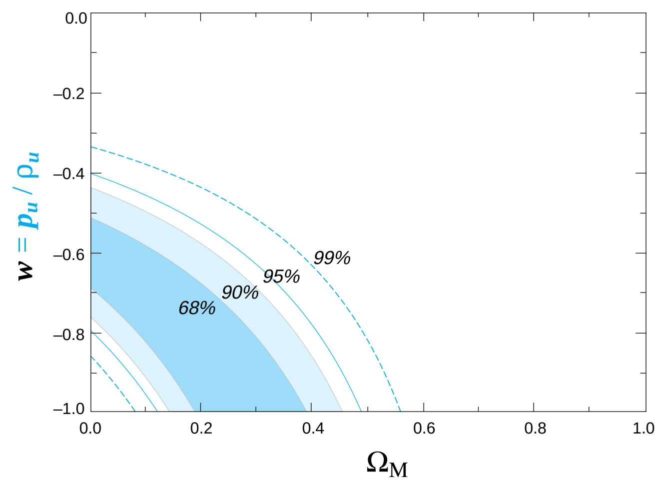

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$\Omega_M = 0.28$ $\pm$ 0.09 statistical $\pm$ 0.05 systematic
$\Omega_\Lambda = 0.72$

Score Card of Uncertainties on $(\Omega_{M}^{flat}, \Omega_{\Lambda}^{flat}) = (0.28, 0.72)$

Statistical

☑	high-redshift SNe	0.05
☑	low-redshift SNe	0.065
	Total	***0.085***

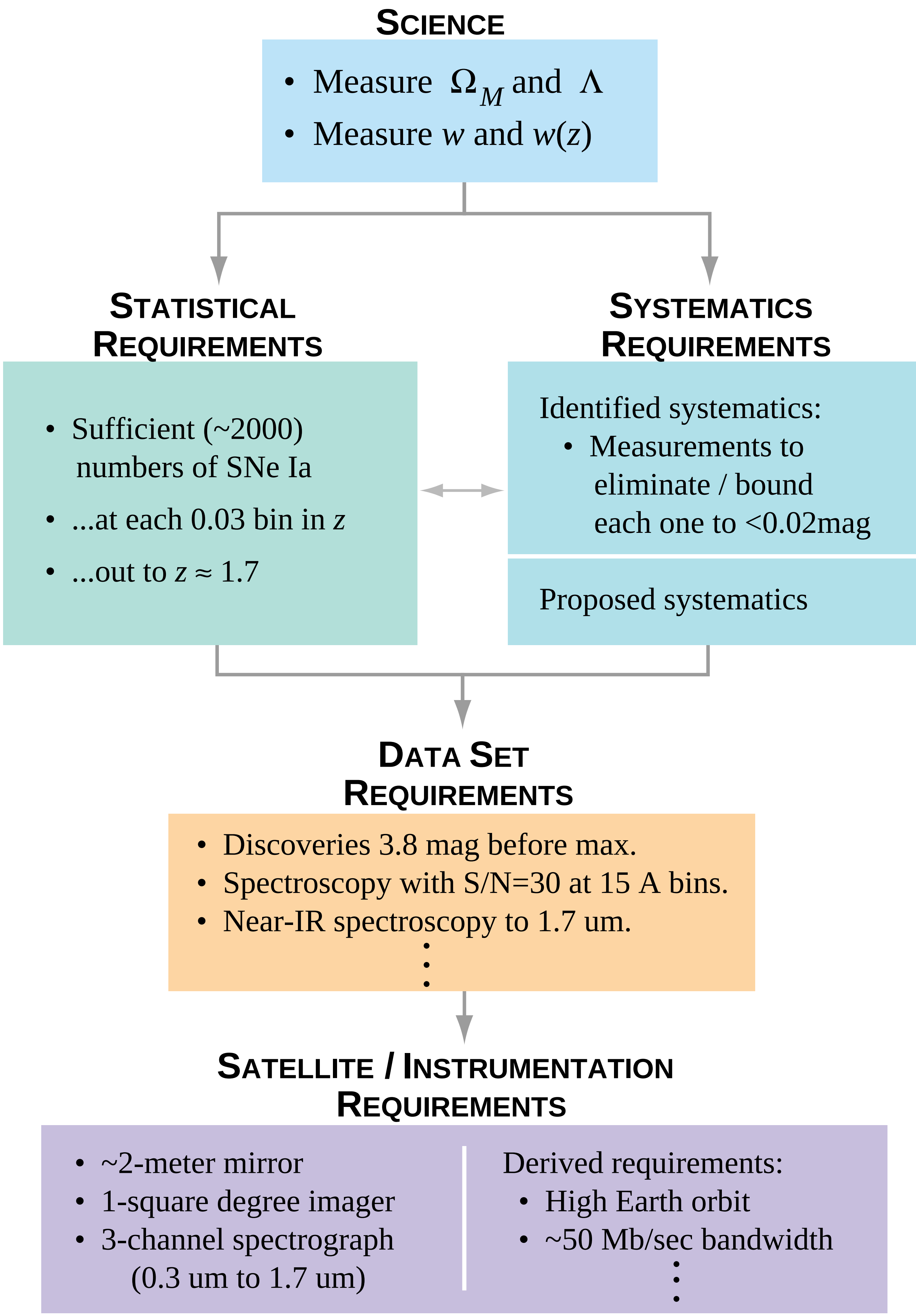
Systematic

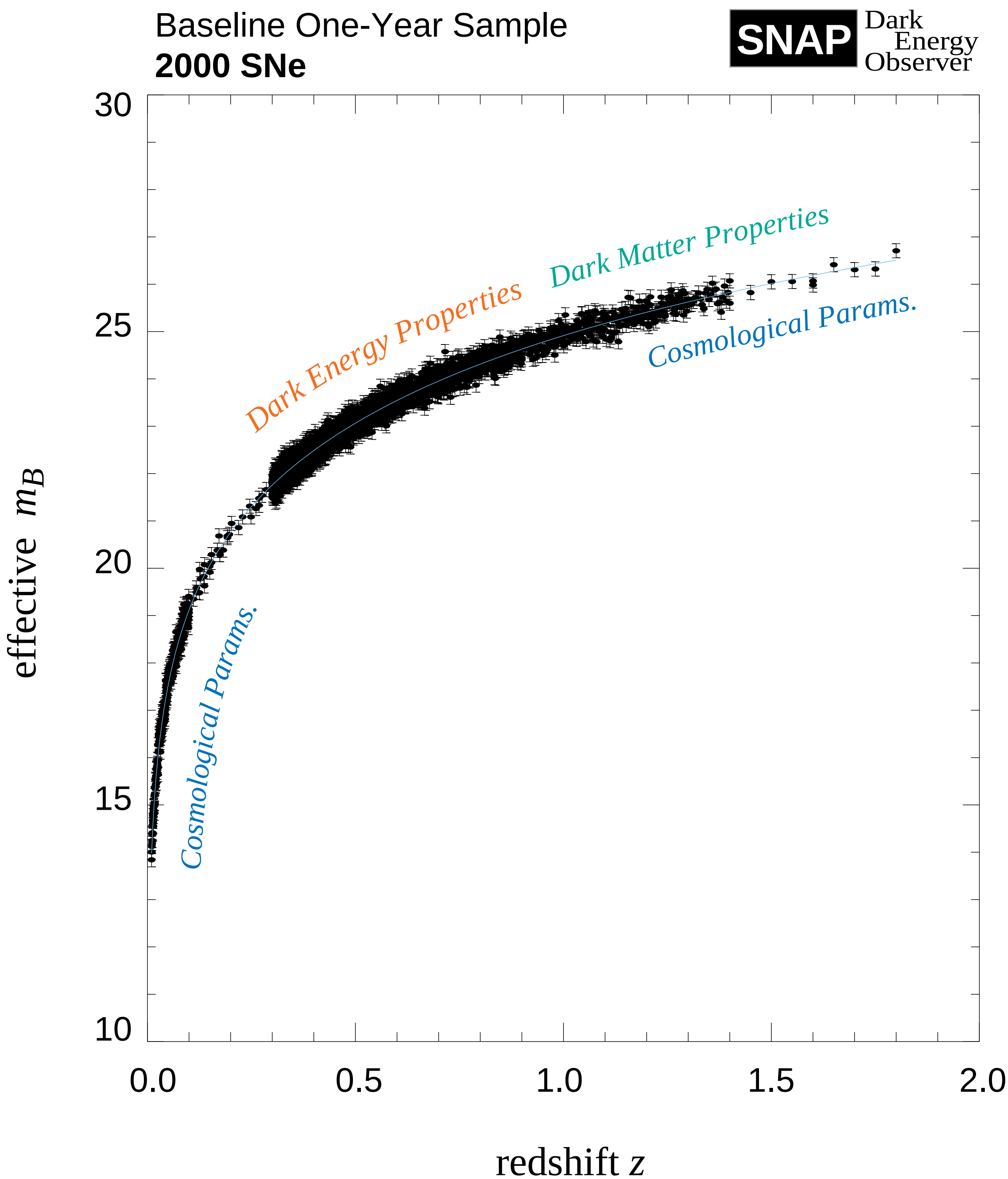
☑	dust that reddens $R_B(z=0.5) < 2\ R_B(\text{today})$	< 0.03
	evolving grey dust	
?	clumpy	
?	same for each SN	
☑	Malmquist bias difference	< 0.04
?	SN Ia evolution shifting distribution of prog mass/metallicity/C-O/..	
☑	K-correction uncertainty including zero-points	< 0.025
	Total identified entities/processes	***0.05***

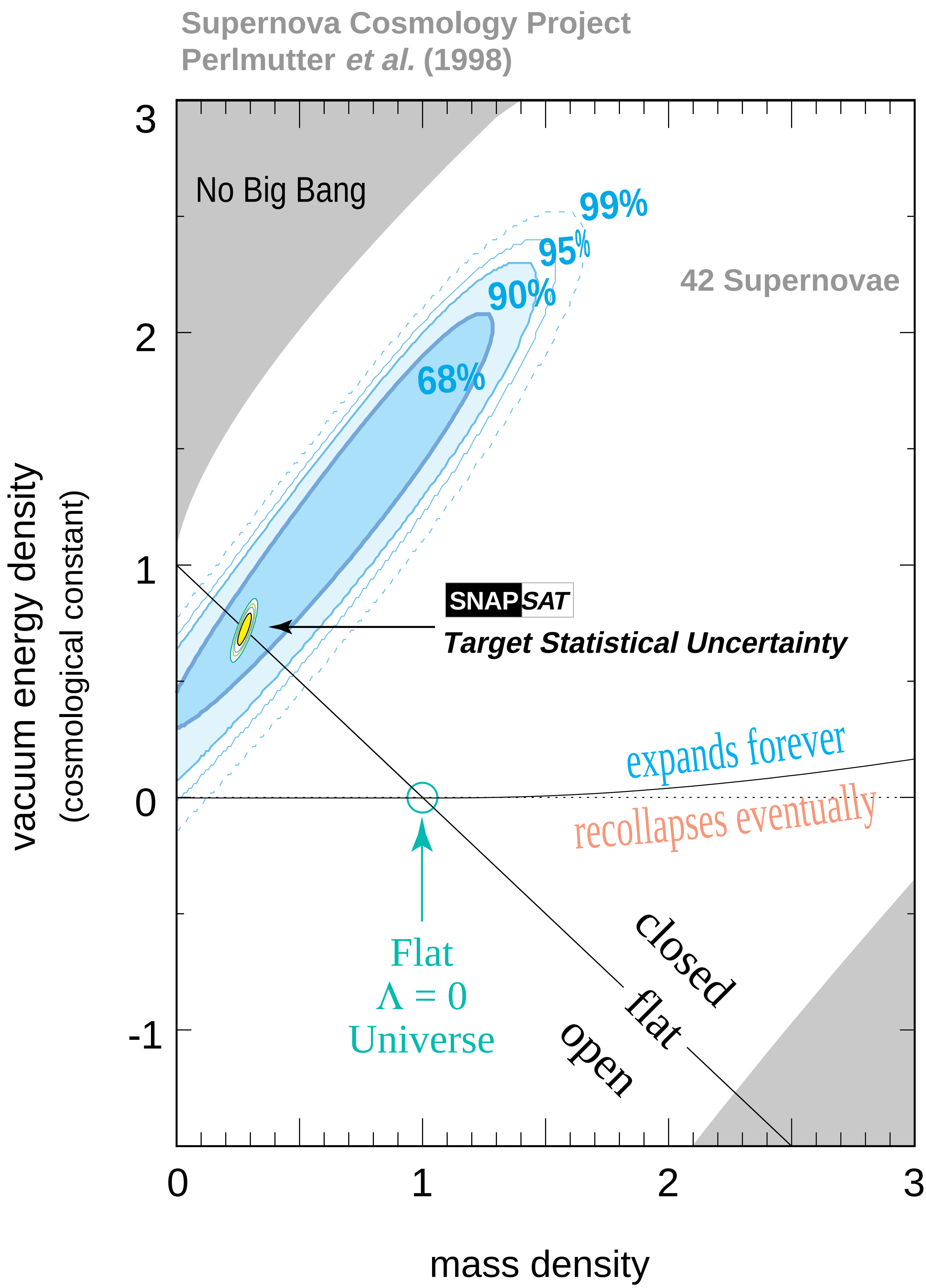
Cross-Checks of sensitivity to

☑	Width-Luminosity Relation	< 0.03
☑	Non-SN Ia contamination	< 0.05
☑	Galactic Extinction Model	< 0.04
☑	Gravitational Lensing by clumped mass	< 0.06

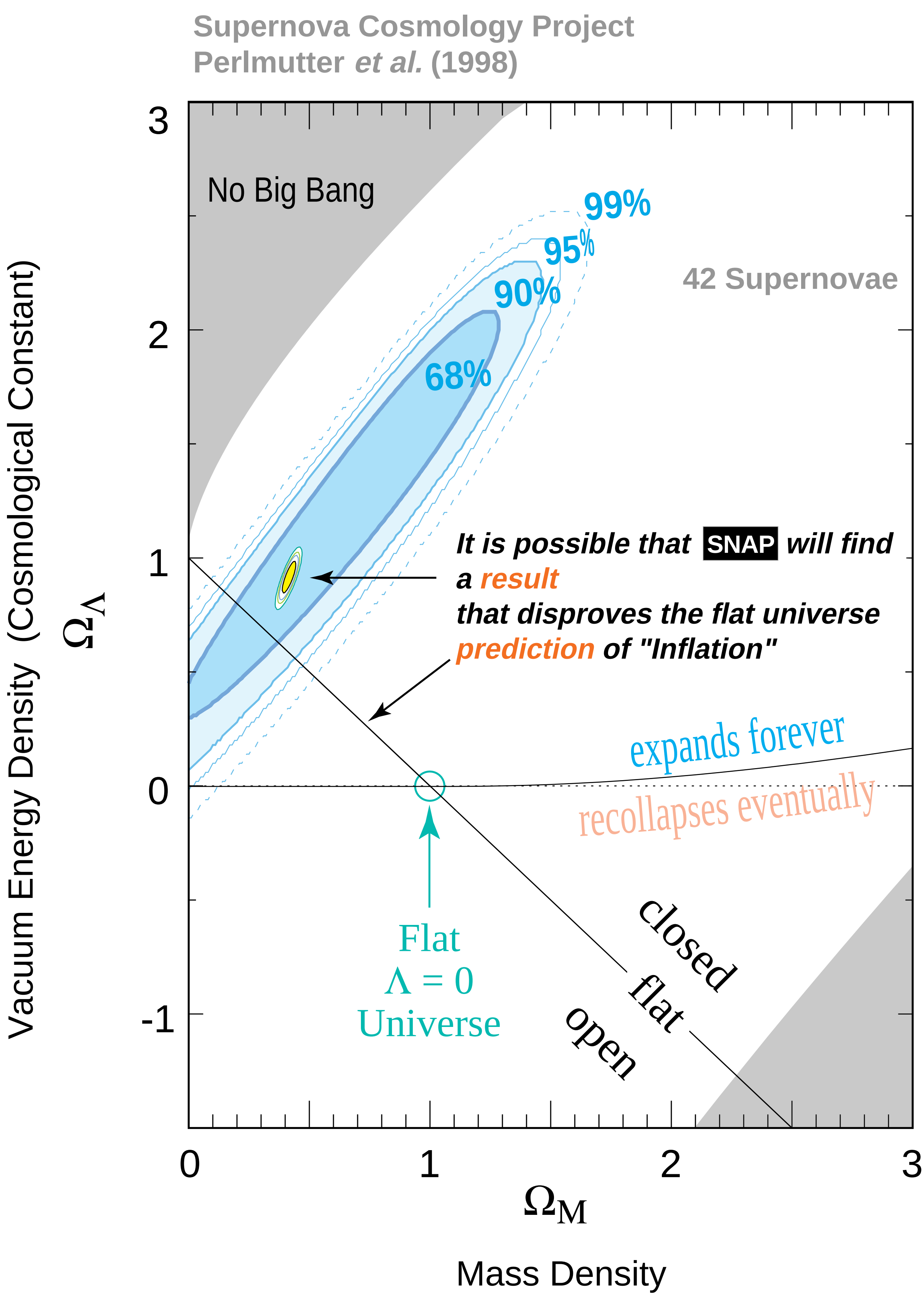
Perlmutter *et al.* (1998)
astro-ph/9812133


SCIENCE
• Measure Ω_M and Λ
• Measure w and $w(z)$
STATISTICAL REQUIREMENTS
• Sufficient (~2000) numbers of SNe Ia
• ...at each 0.03 bin in z
• ...out to $z \approx 1.7$
SYSTEMATICS REQUIREMENTS
Identified systematics:
• Measurements to eliminate / bound each one to <0.02mag
Proposed systematics
DATA SET REQUIREMENTS
• Discoveries 3.8 mag before max.
• Spectroscopy with S/N=30 at 15 A bins.
• Near-IR spectroscopy to 1.7 um.
⋮
SATELLITE / INSTRUMENTATION REQUIREMENTS
• ~2-meter mirror
• 1-square degree imager
• 3-channel spectrograph (0.3 um to 1.7 um)
Derived requirements:
• High Earth orbit
• ~50 Mb/sec bandwidth
⋮


Baseline One-Year Sample
2000 SNe
SNAP Dark Energy Observer
Dark Energy Properties
Dark Matter Properties
Cosmological Params.
Cosmological Params.
effective m_B
redshift z
30
25
20
15
10
0.0
0.5
1.0
1.5
2.0



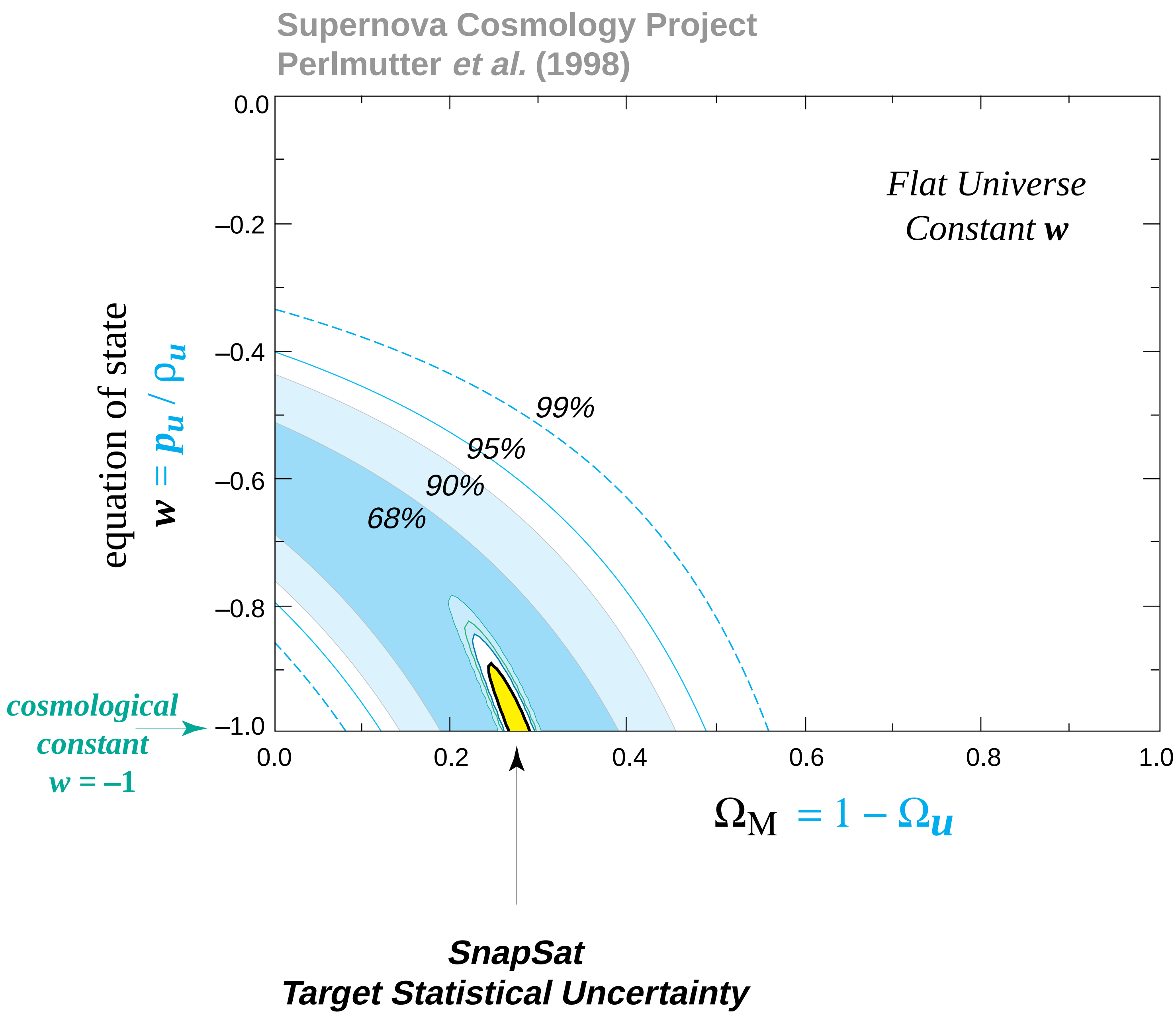
Supernova Cosmology Project
Perlmutter et al. (1998)
No Big Bang
99%
95%
90%
68%
42 Supernovae
SNAPSAT
Target Statistical Uncertainty
expands forever
recollapses eventually
Flat
Λ = 0
Universe
closed
flat
open
vacuum energy density
(cosmological constant)
mass density
3
2
1
0
-1
0
1
2
3



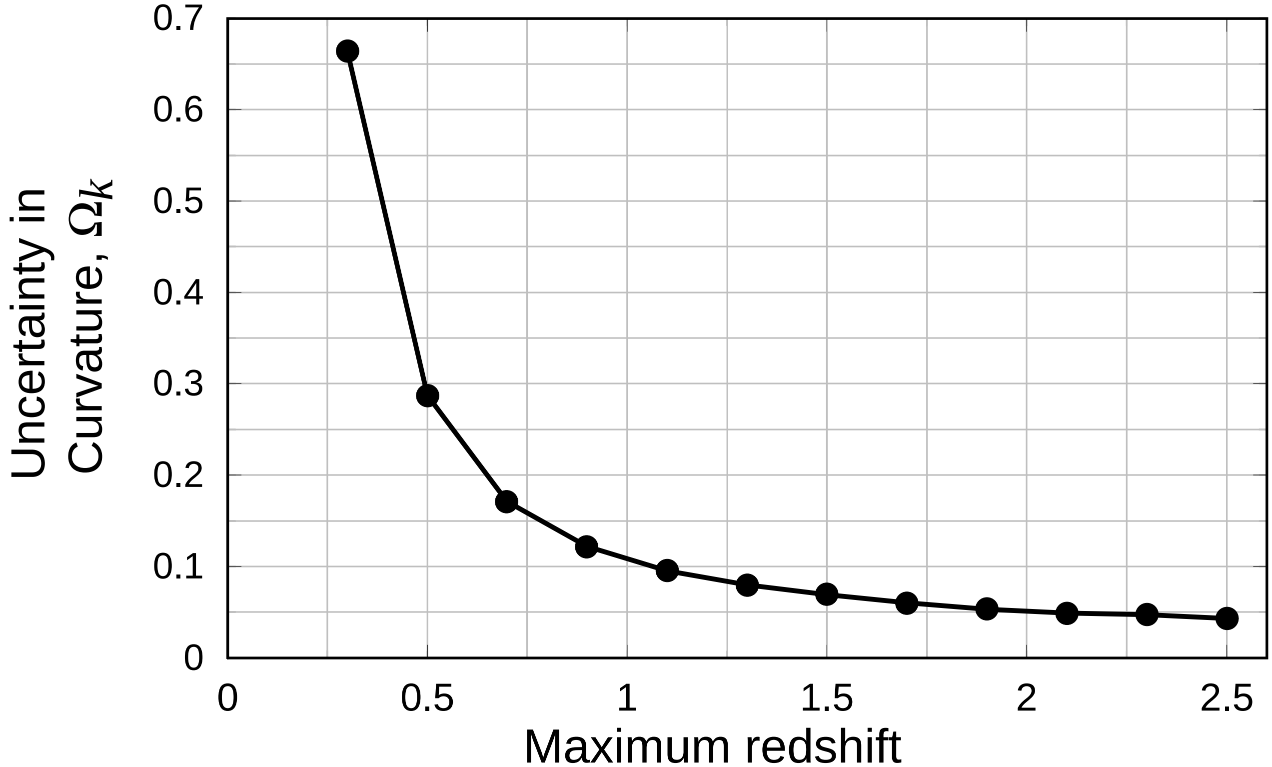
Supernova Cosmology Project
Perlmutter et al. (1998)
No Big Bang
99%
95%
90%
68%
42 Supernovae
It is possible that SNAP will find a result that disproves the flat universe prediction of "Inflation"
expands forever
recollapses eventually
closed
flat
open
Flat
Λ = 0
Universe
Vacuum Energy Density (Cosmological Constant)
Ω_Λ
Ω_M
Mass Density
3
2
1
0
-1
0
1
2
3

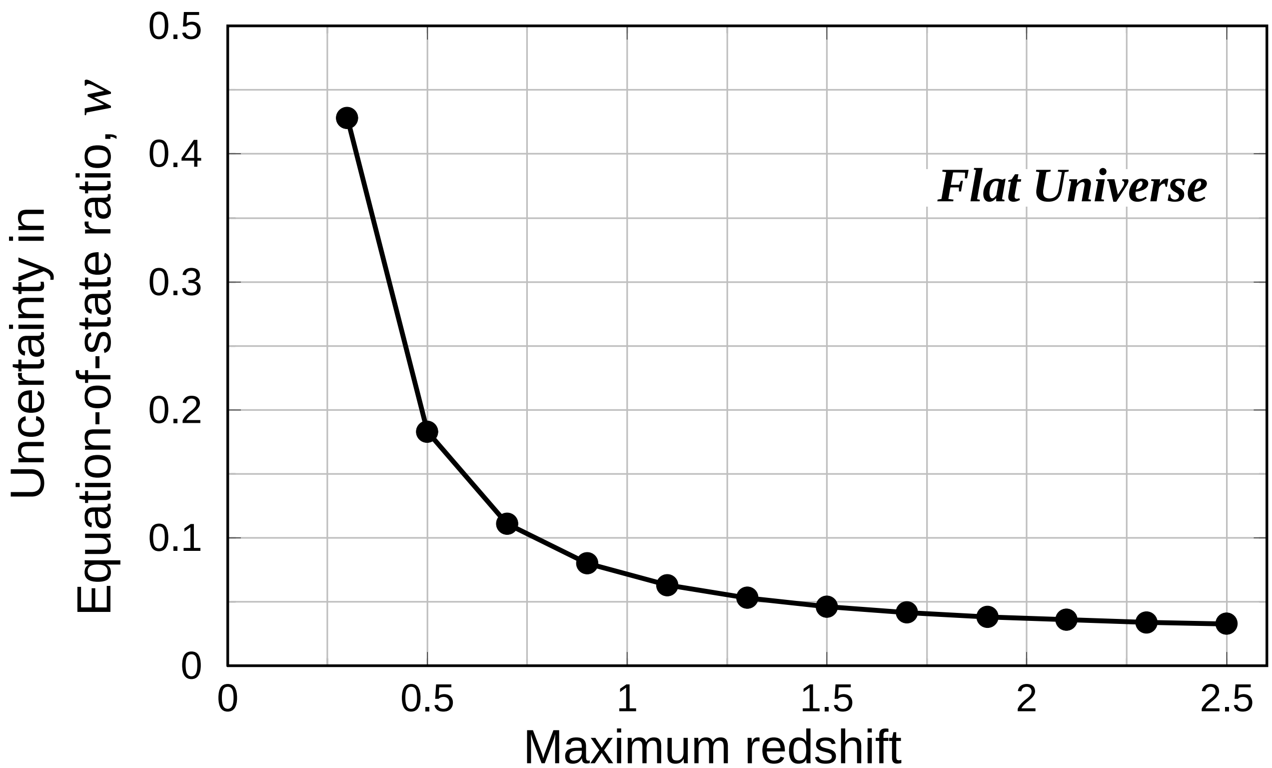
Dark Energy

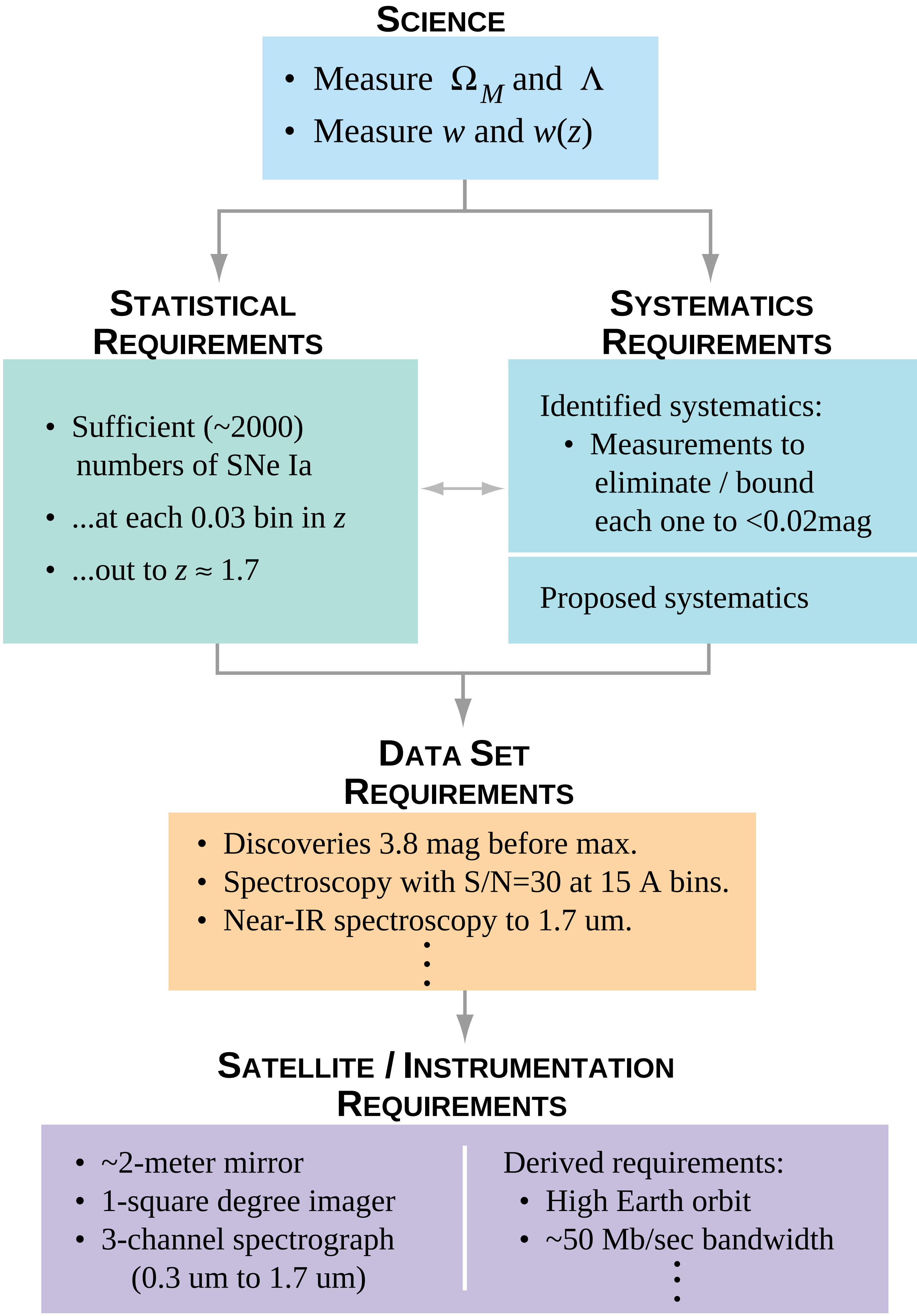
Unknown Component, Ω_u, of Energy Density



How do uncertainties improve as we extend the range of redshifts?






Science
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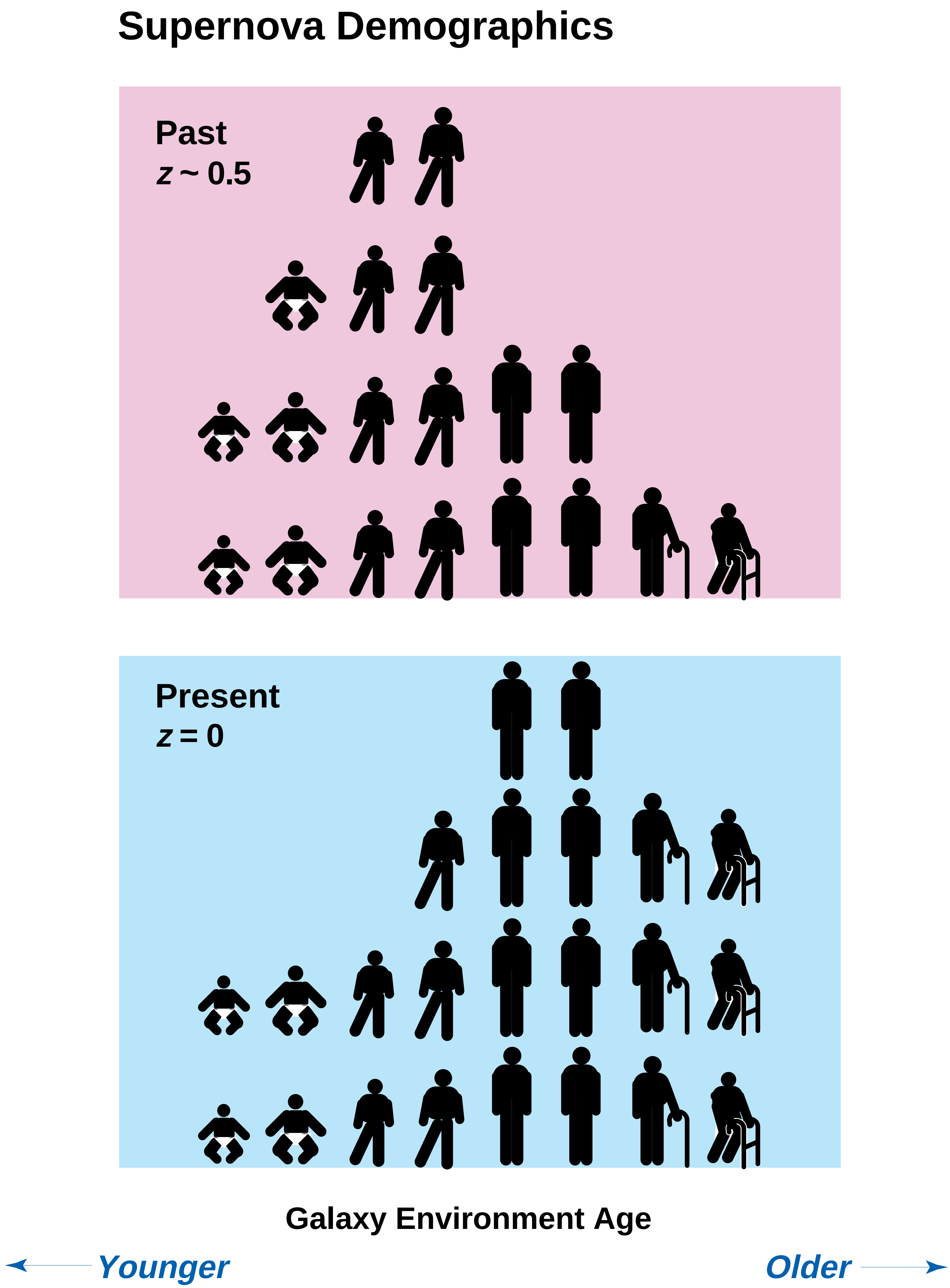
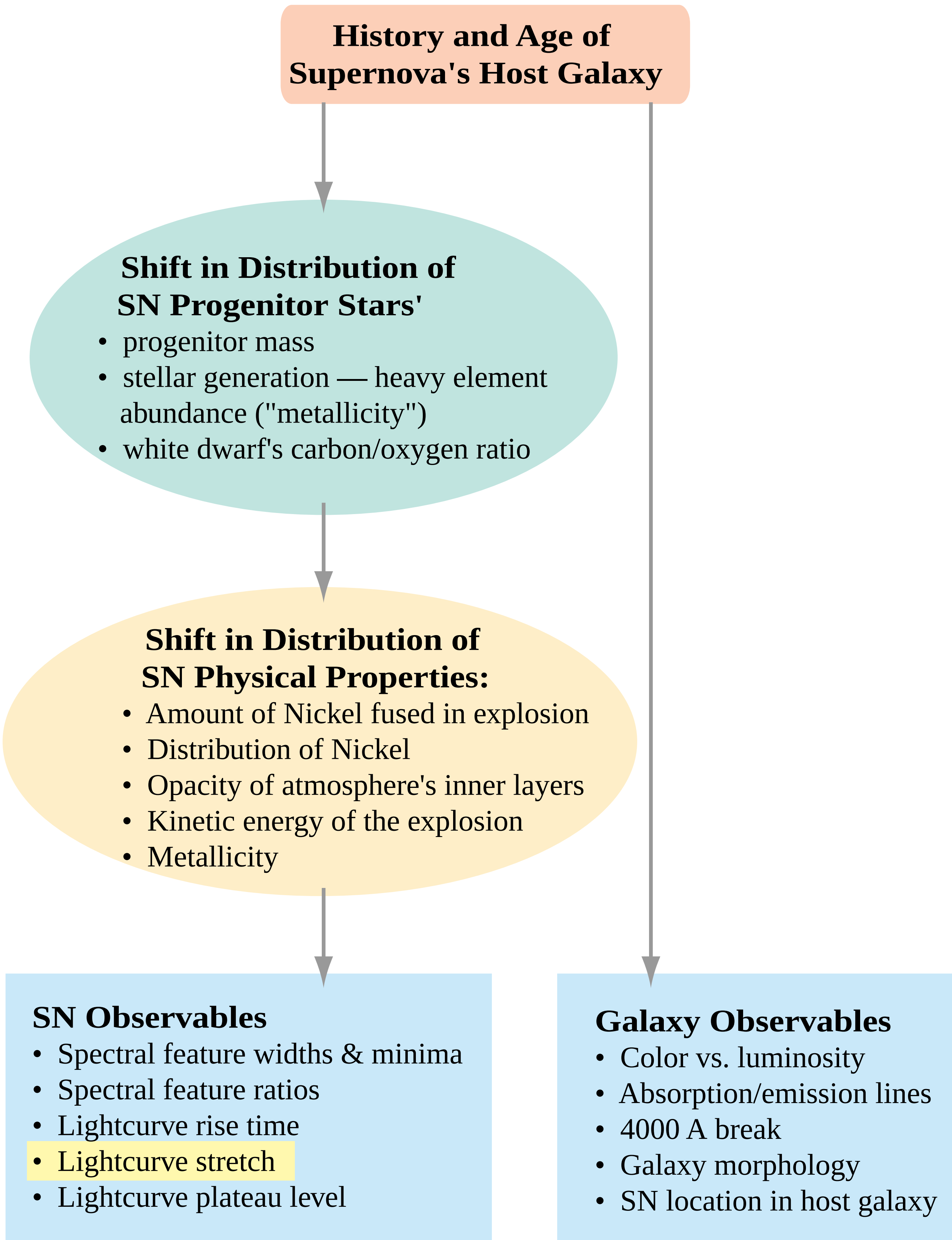
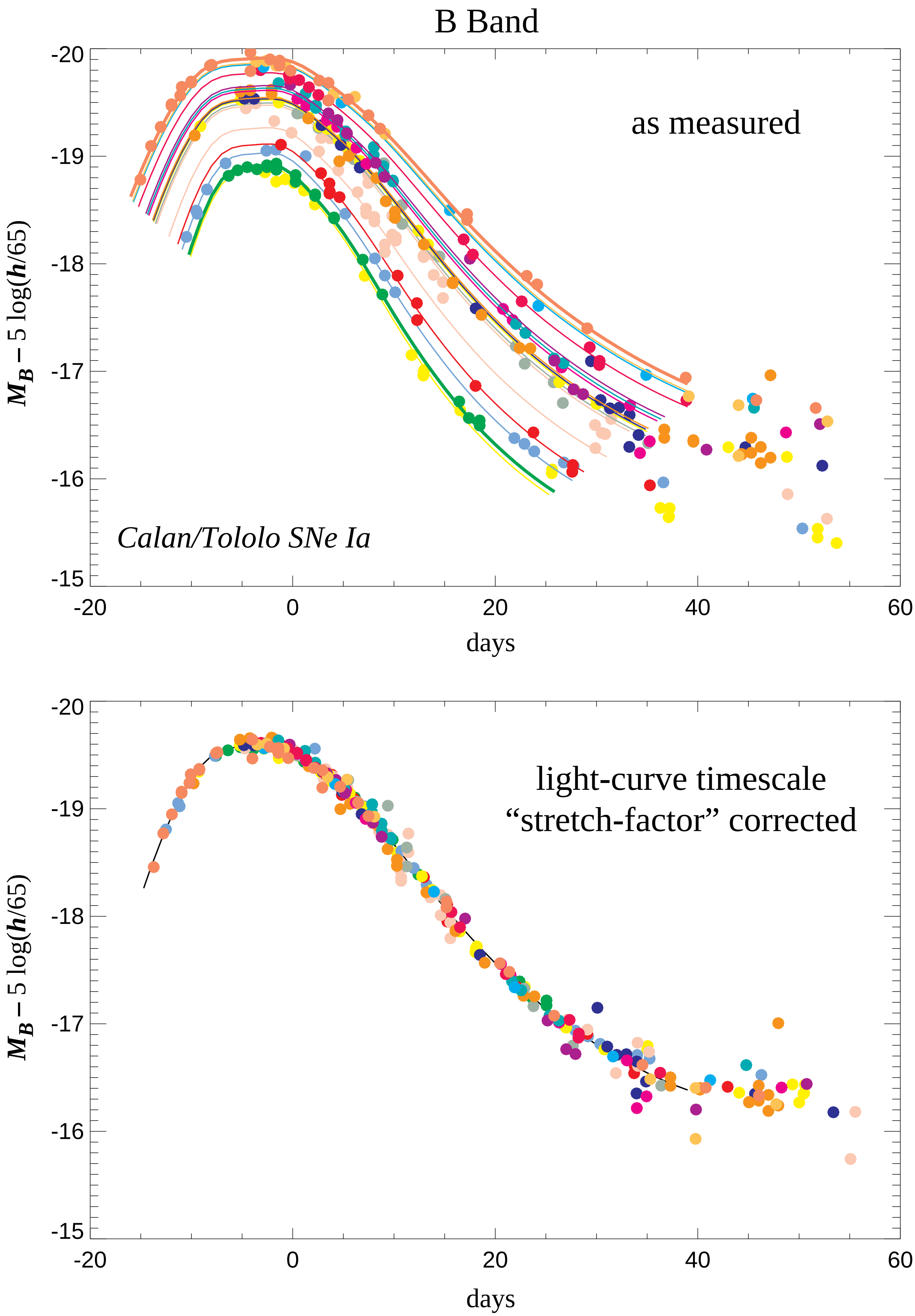
astro-ph/9812133


Supernova Demographics
Past
z ~ 0.5
Present
z = 0
Galaxy Environment Age
Younger
Older

Control of Evolution Systematics:
Matching Supernovae

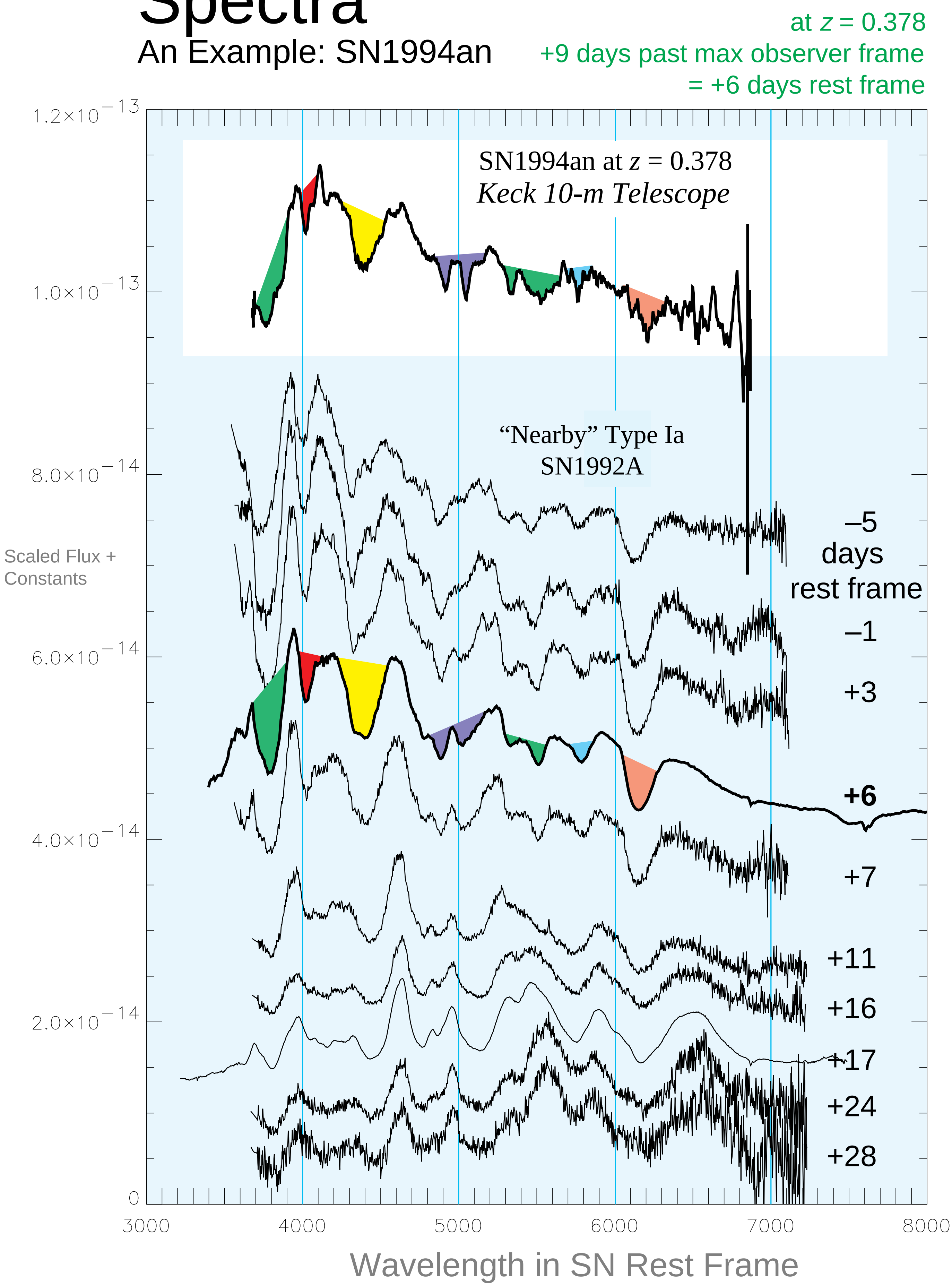




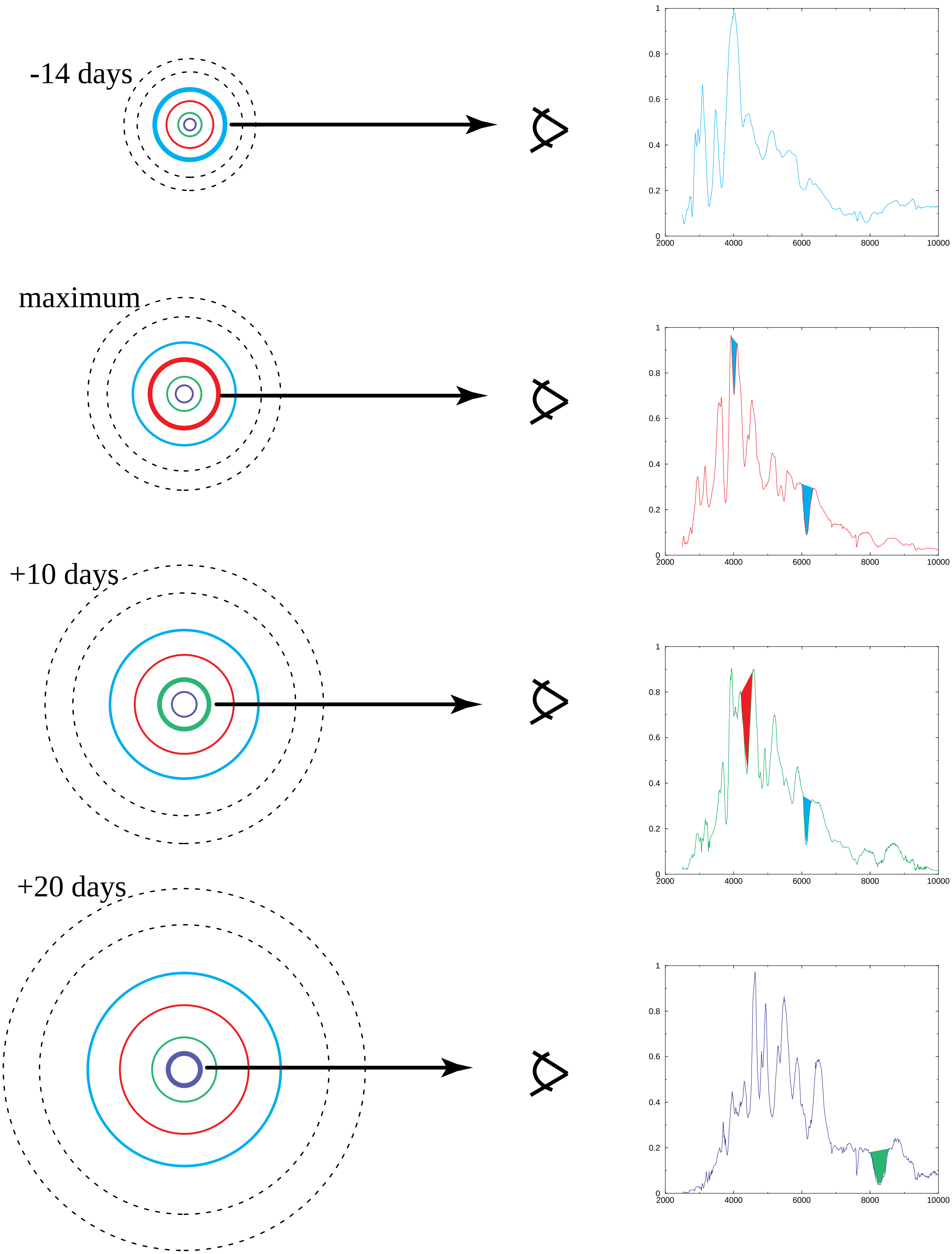
Kim, *et al.* (1997)

Spectra

An Example: SN1994an

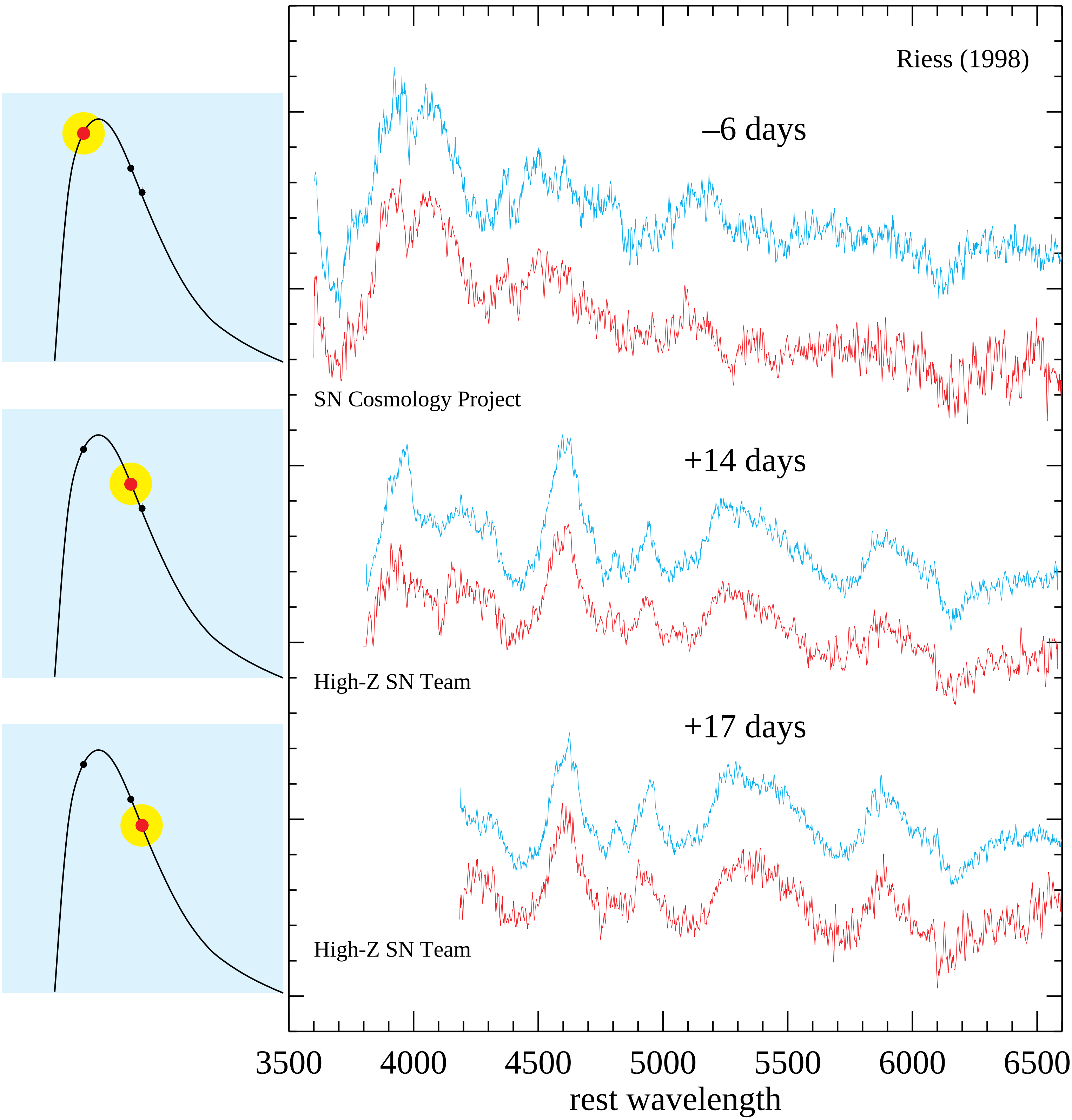


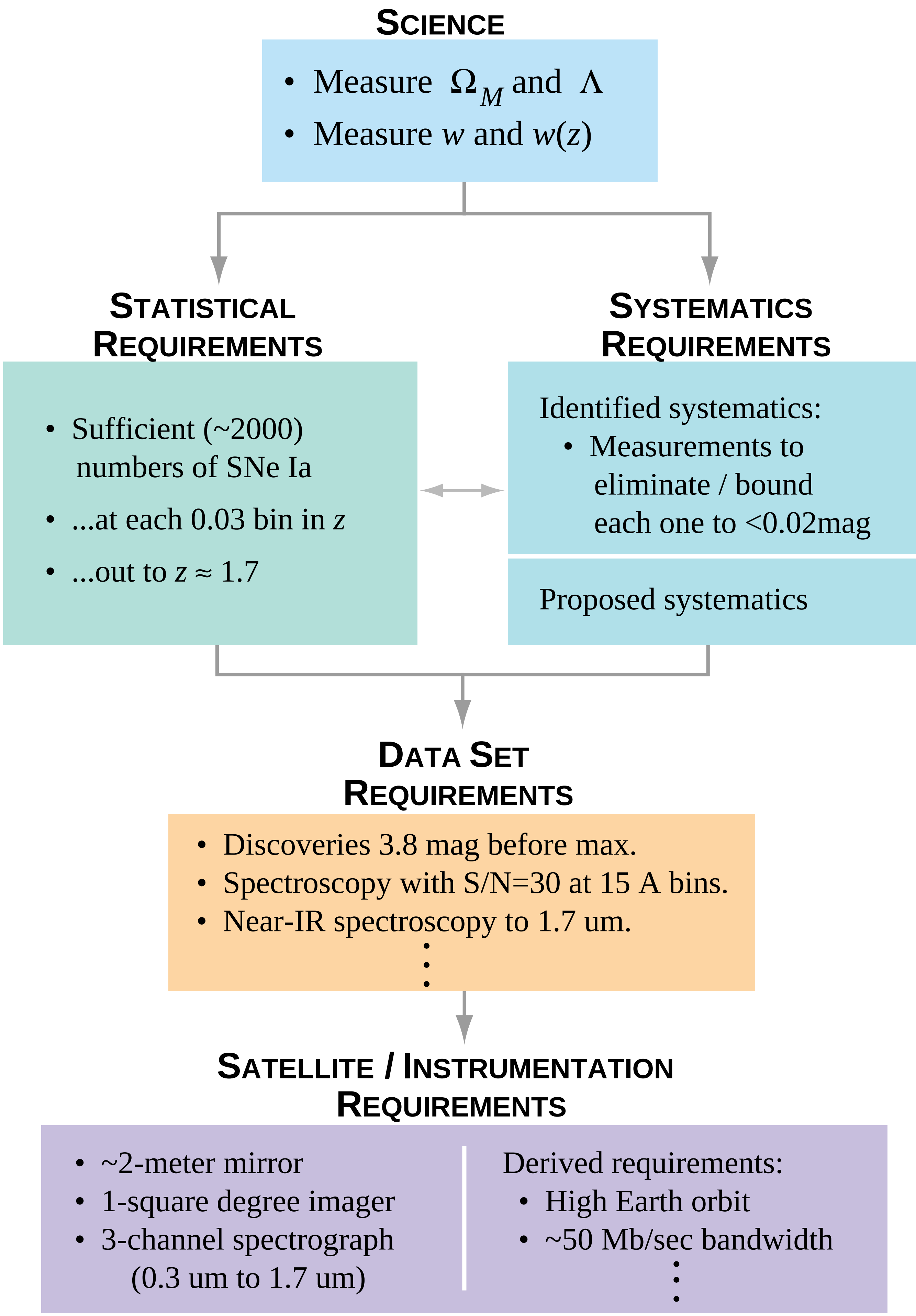
The time series of spectra is a “CAT Scan” of the Supernova



Time Series of Low-Redshift and High-Redshift Spectra

SN 1997ex at z = 0.36
Supernova Cosmology Project

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SNAP Dark Energy Observer

supernova / acceleration probe

satellite overview

- **1.8m aperture telescope**

  Can reach very distant SNe.

- **1 square degree mosaic camera, 1 billion pixels**

  Efficiently studies large numbers of SNe.

- **3-channel spectroscopy, 0.3um -- 1.8um**

  Detailed analysis of each SN.

MIDEX+ class satellite:

Dedicated instrument.

Designed to repeatedly observe an area of sky.

Essentially no moving parts.

4-year construction cycle.
3-year operation for experiment
(lifetime open-ended).

Baseline observing strategy

Continuous monitoring (every 4 days) of
~2 sq. deg. to m_{AB} (1μm) ≈ 30
~20 sq. deg. to m_{AB} (1μm) ≈ 28.5

Discover *every* SN in these fields to m_{AB}^{limit}

One-year baseline data package

Full sample of 2000 SNe between z = 0.3 and 1.7

Discovery within ~2 days of explosion (i.e. ~2 weeks before max).
Most dense coverage between z = 0.3 and 1.0

- Spectra at max for all SNe. (0.3 -- 1.8um)
- Lightcurve points at least 1/week (restframe) from -15 to +60 days (restframe)

Subsample of 200 SNe from the full sample

Selected to span
- lightcurve timescales
- galaxy environments (morphology, galactocentric radius)
- redshifts

- Spectra at least 2/week (restframe) first month, 1/week (restframe) later
- Synthetic "filter-tuned" photometry from spectra for perfect K-corrections

Feasibility

Baseline design feasibility established in a preliminary study with Ball Aerospace, with reference to existing satellite missions.

- Top-down cost estimates.

- Orbit trade study: launch vehicle, mass-to-orbit, thermal control, cosmic-ray load, continuous observing duty cycle, telemetry rates, and power budget.

- Optical designs.

- Pointing requirements: fast-steering mirror avoids need to stabilize spacecraft.

- CCDs: fabrication, radiation hardness, mounting.

- Complex readout electronics.

- Observing schedule tradeoffs.

Why a New Satellite?

Ground-based telescopes:

A dedicated 8-meter with 9-square-degree imager...

- cannot discover SNe within 2 restframe days of explosion beyond $z = 0.6$.
- cannot measure SN plateau level (>45 days after peak) beyond $z = 0.7$.
- even limiting redshifts to $z = 0.6$, can only discover fewer than 300 SNe/year.

Space-based (HST or NGST) telescopes:

NGST has a supernova program planned, but targets different and complementary science — higher redshifts ($z \gg 1$), fewer (~100) SNe and fewer observations (~4) per SN.

- NGST 16-square-arcminute field of view would require many years of dedicated searching to discover comparable numbers of SNe in the target redshift range.
- Using NGST to obtain spectroscopy of the SN discovered by SNAP would be wasteful: Most of the time for over half a year would be spent slewing the NGST, with the shutter open only a small fraction of the time.

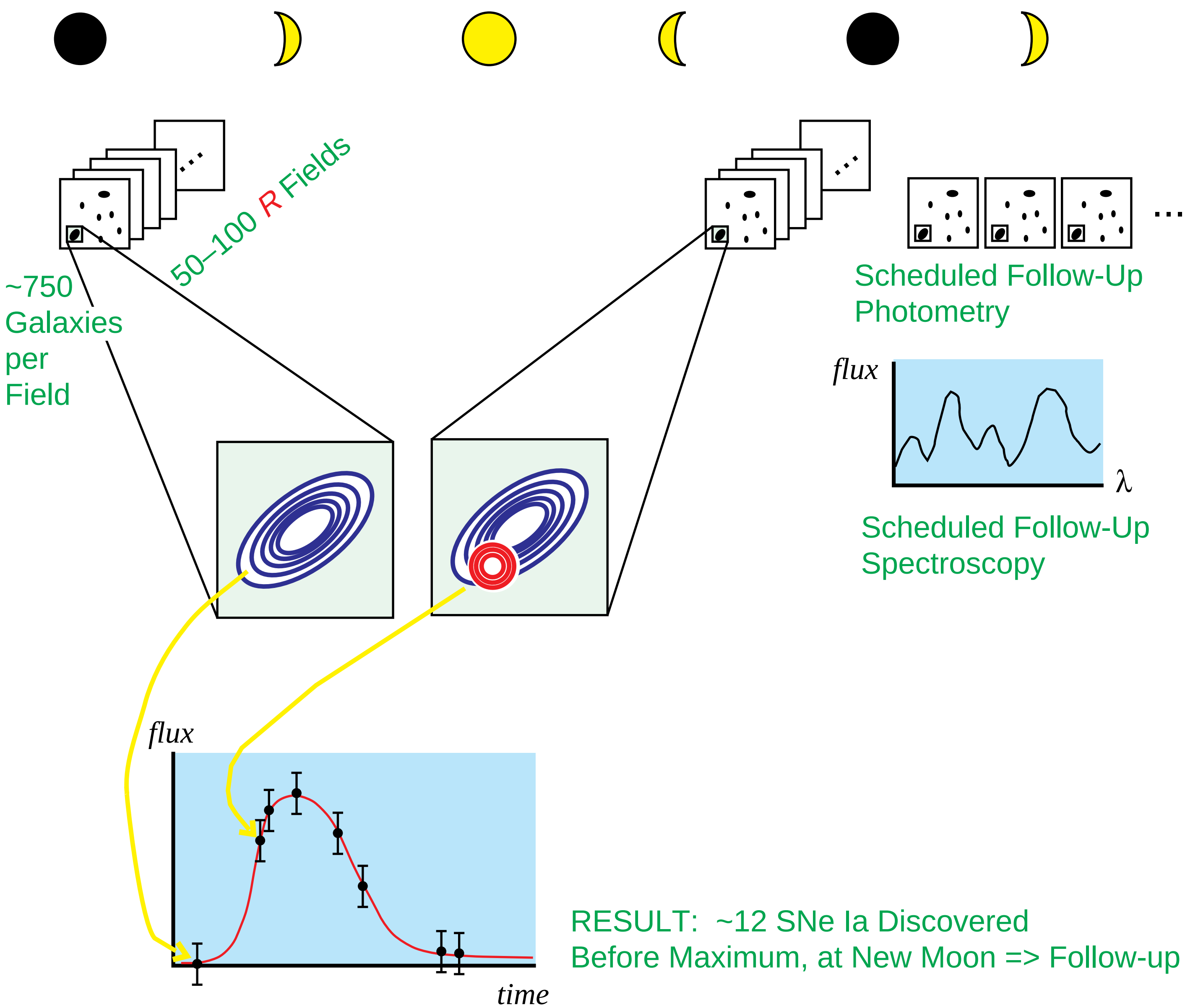
Baade (1938)	Supernovae at max as a Standard Candle for cosmological measurements
Tammann (1979, 1984) Colgate (1979)	Type I SNe to measure deceleration parameter, q0 (with HST!)
Nørgaard-Nielsen et al. (1989)	Intensive search for high-redshift SNe finds one Type Ia in two years (several weeks past max)

Problems

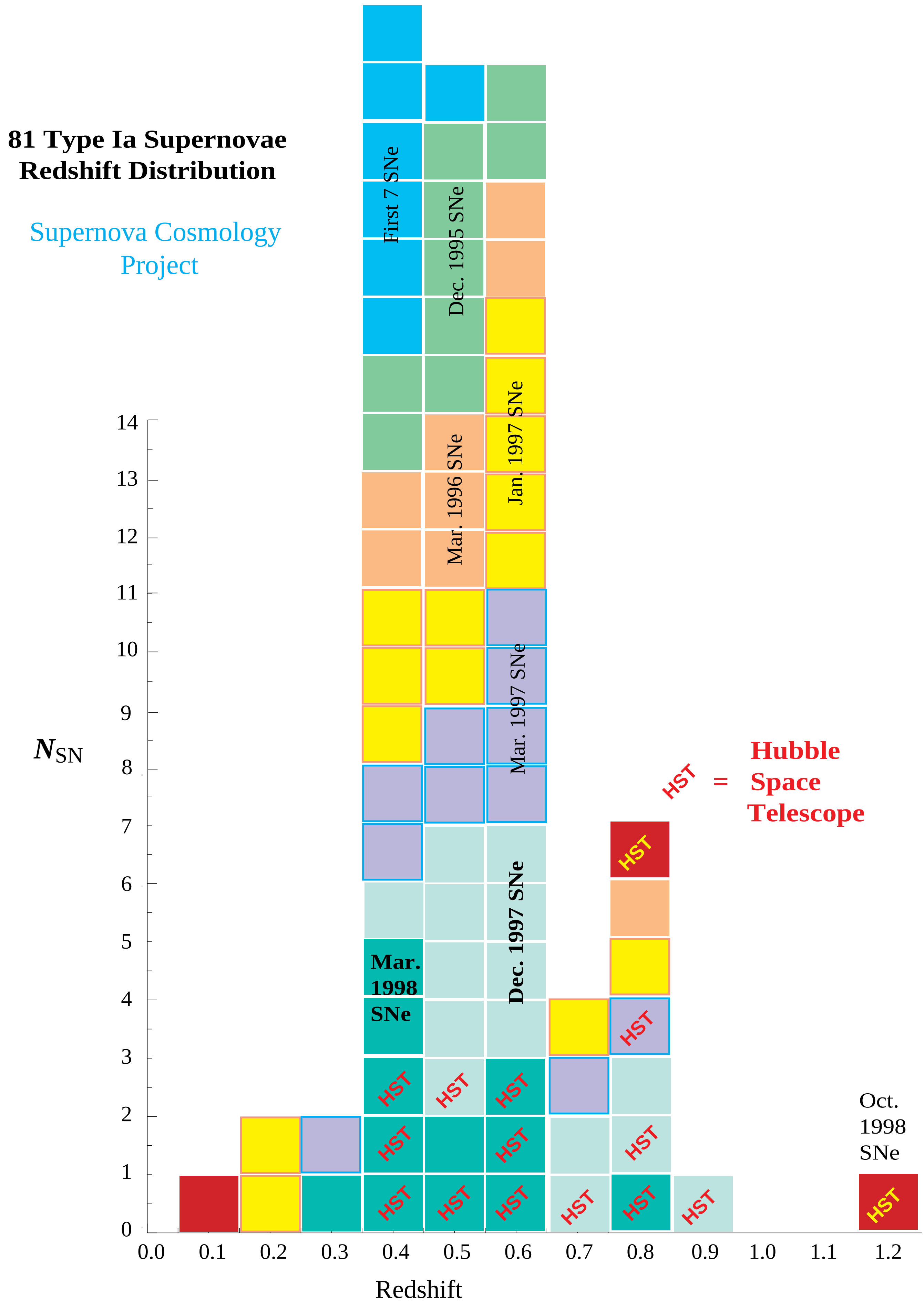
with Type Ia Supernovae as a tool for cosmology

Rare	~1 / 500 years / galaxy
Random	can't schedule telescope time or plan discoveries at new moon
Rapid	difficult to catch on the rise

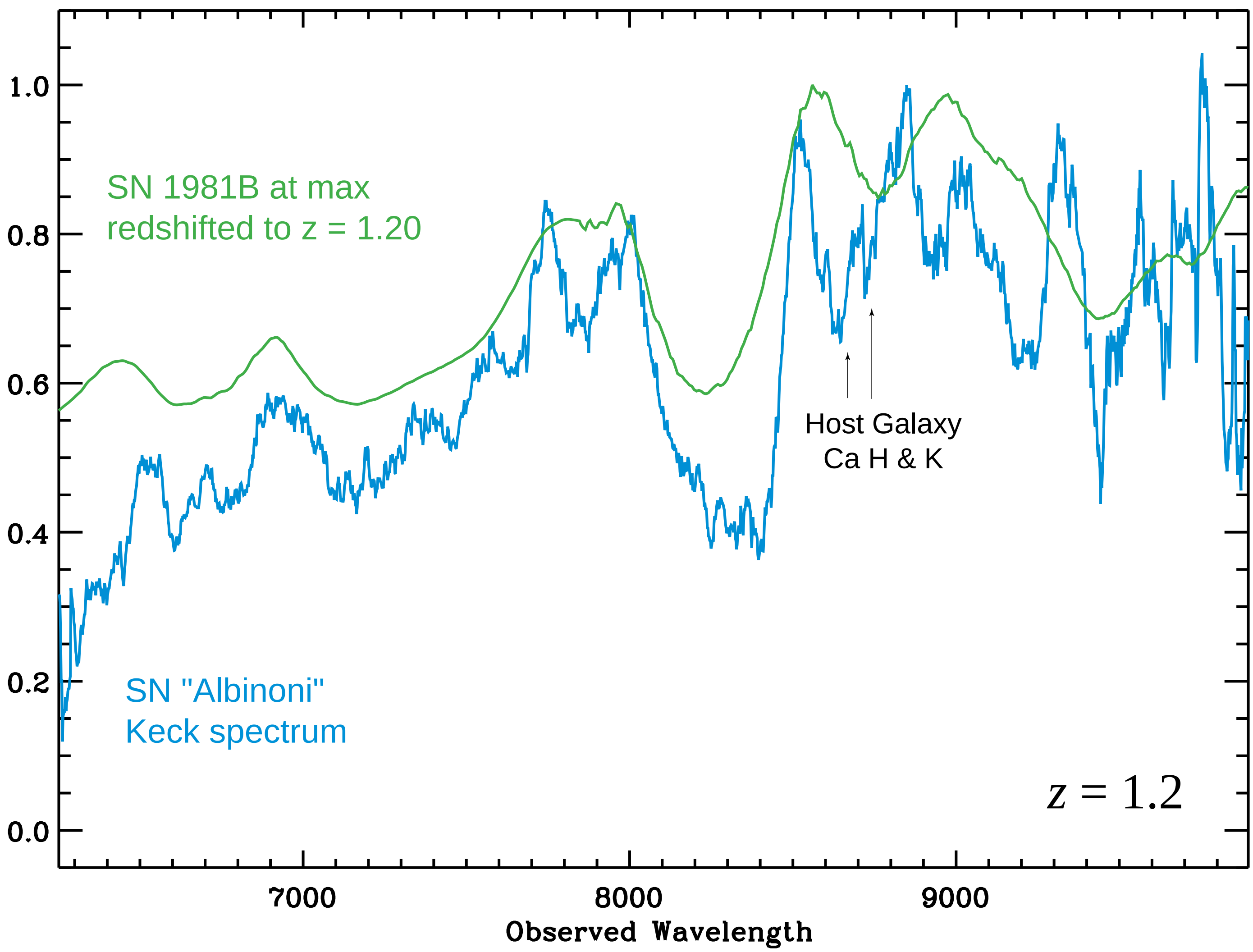
Search Strategy Perlmutter et al. (1996a)



RESULT: ~12 SNe Ia Discovered
Before Maximum, at New Moon => Follow-up



81 Type Ia Supernovae
Redshift Distribution
Supernova Cosmology
Project
First 7 SNe
Dec. 1995 SNe
Mar. 1996 SNe
Jan. 1997 SNe
Mar. 1997 SNe
Dec. 1997 SNe
Mar. 1998 SNe
Oct. 1998 SNe
HST = Hubble Space Telescope
N_{SN}
Redshift
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2



SN 1981B at max
redshifted to z = 1.20
SN "Albinoni"
Keck spectrum
Host Galaxy
Ca H & K
z = 1.2
1.0
0.8
0.6
0.4
0.2
0.0
7000
8000
9000
Observed Wavelength

Why a New Satellite?

Ground-based telescopes:

A dedicated 8-meter with 9-square-degree imager...

- cannot discover SNe within 2 restframe days of explosion beyond $z = 0.6$.
- cannot measure SN plateau level (>45 days after peak) beyond $z = 0.7$.
- even limiting redshifts to $z = 0.6$, can only discover fewer than 300 SNe/year.

Space-based (HST or NGST) telescopes:

NGST has a supernova program planned, but targets different and complementary science — higher redshifts ($z \gg 1$), fewer (~100) SNe and fewer observations (~4) per SN.

- NGST 16-square-arcminute field of view would require many years of dedicated searching to discover comparable numbers of SNe in the target redshift range.
- Using NGST to obtain spectroscopy of the SN discovered by SNAP would be wasteful: Most of the time for over half a year would be spent slewing the NGST, with the shutter open only a small fraction of the time.

SNAP Dark Energy Observer

supernova acceleration probe

complementary science

Cosmological Parameters...

Type II supernova expanding photosphere
Weak lensing
Strong lensing statistics. Ω_Λ
Galaxy clustering, $P(k)$
$z > 1$ clusters and associated lensing
. . .

...and Beyond

GRB optical counterparts: rates, lightcurves, and spectra
MACHO optical counterparts by proper motion
Galaxy populations and morphology to co-added $m \approx 32$
Target selection for NGST
Kuiper belt objects
Supernova rates, star formation rates
Supernova phenomenology studies
Low surface brightness galaxies, luminosity function
. . .

Using DOE/NSF-developed science and technology,

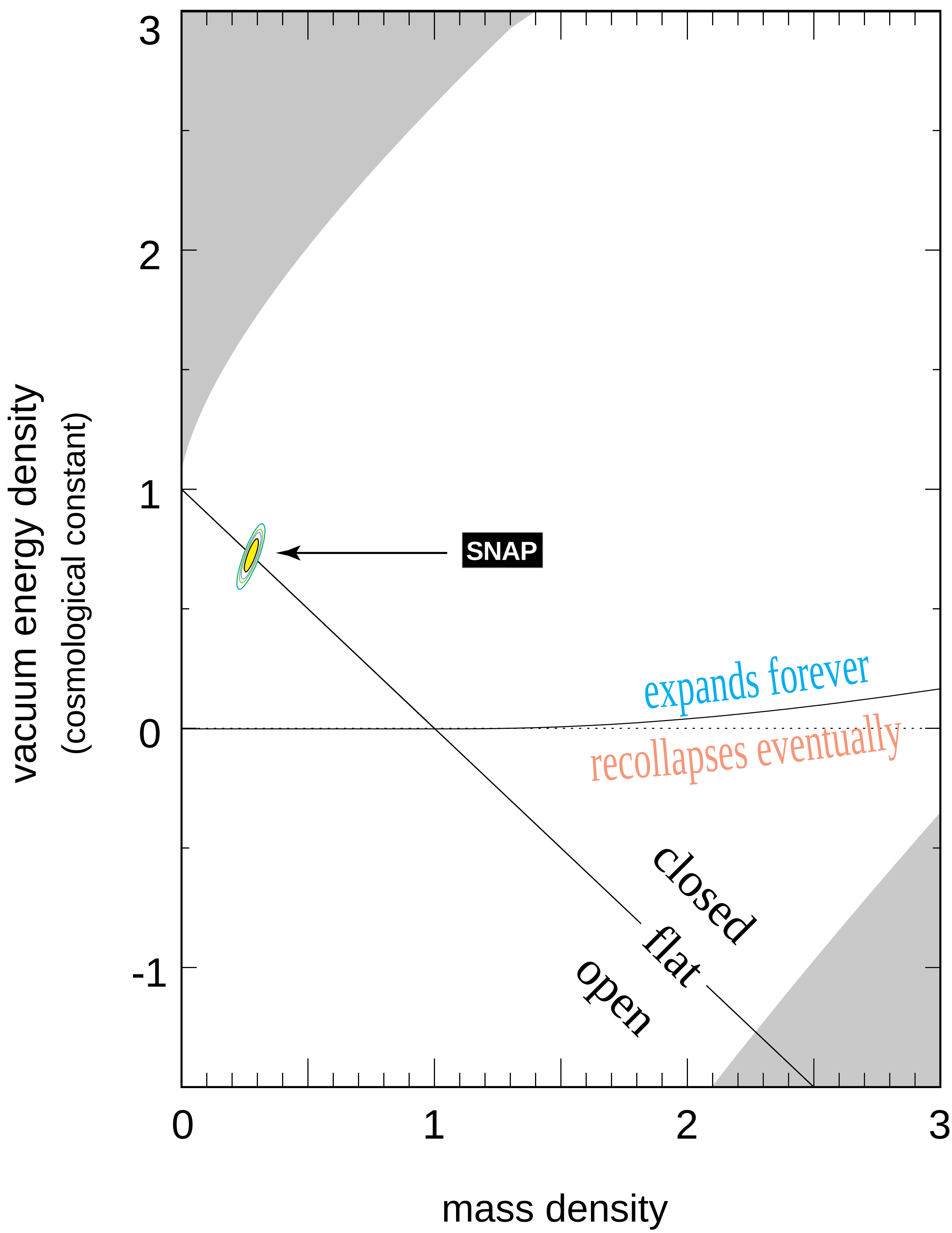
Particle physics/cosmology theory:
Inflation, Quintessence, BBN...
Supernova cosmology measurements
Keck telescope
CMB studies
CCD technology
HEP large, complex detector experience
Supernova theory/simulations
Supercomputer centers / Grand challenges

we have an unusual opportunity
to answer fundamental questions of physics

Is the universe infinite?
Is space curved?
What is the fate of the universe?
What is the "Dark Energy" that is causing
the universe expansion to accelerate?

with a definitive, precision cosmology measurement.

The first complete calibrated supernova dataset,
2 orders of magnitude larger statistics (>2000 SNe),
extending much farther in distance and in time.
A ±0.03 measurement of the mass density.
A ±0.05 measurement of the vacuum energy density.
A ±0.06 measurement of the curvature.
A ±0.05 measurement of the Equation of State
of the "Dark Energy"



vacuum energy density
(cosmological constant)
mass density
SNAP
expands forever
recollapses eventually
closed
flat
open
3
2
1
0
-1
0
1
2
3